FINAL TECHNICAL REPORT

LATE HOLOCENE EARTHQUAKE HISTORY OF THE BRAWLEY FAULT: DID THE 1690 SAN ANDREAS EARTHQUAKE ALSO RUPTURE THE BRAWLEY FAULT

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Late Holocene Earthquake History of the Brawley Fault: Did the 1690 San Andreas Earthquake Also Rupture the Brawley Fault

This final technical report is written as a manuscript, soon to be submitted for publication, entitled "Recent Escalation in Slip across the Brawley Fault Zone, Imperial Valley, California: Decades versus Centuries" by Aron J. Meltzner, Thomas K. Rockwell, and Lewis A. Owen

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Recent Escalation in Slip across the Brawley Fault Zone, Imperial Valley, California: Decades versus Centuries

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ABSTRACT

The Brawley fault zone (BFZ) and the Brawley Seismic Zone comprise the principal transfer zone accommodating strain between the San Andreas and Imperial faults in southernmost California. The BFZ ruptured along with the Imperial fault in the 1979 M_W 6.4 and the 1940 M_W 6.9 earthquakes, although in each case only minor slip apparently occurred on the BFZ; several other episodes of slip and creep have been documented on the BFZ historically. Until this study, it has been unclear whether the past few decades reflect average behavior of the fault. We have opened two trenches and a series of auger boreholes across three strands of the BFZ at Harris Road, and we compare the amount of slip observed historically with the displacements observed in the paleoseismic record. We present evidence, both across the westernmost strand of the BFZ and across the entire BFZ at Harris Road, that the vertical slip rate documented in the 1970s is significantly higher than the long-term average. Across the westernmost strand, the long-term rate is 1.2 (+1.5/–0.5) mm/yr, and the average rate since ca. A.D. 1710 is constrained to be no greater than 2.1 mm/yr; in contrast, the average rate between 1970 and 1988 across that strand was at least 7.7 mm/yr. Likewise, across the entire BFZ, the long-term vertical rate is 2.8 (+4.1/–1.4) mm/yr, whereas the rate increased to at least 11.6 mm/yr between 1970 and 1988. The long-term strike-slip rate cannot be constrained across any strands of the BFZ but may be significant. In contrast to the commonly accepted high sedimentation rates inferred for the entire Imperial Valley, we find that the average sedimentation rate on the downthrown side of the BFZ adjacent to Mesquite Basin, in the millennium preceding the onset of agricultural influences, was at most 3.5 mm/yr.

INTRODUCTION

The Brawley fault zone (BFZ) and the Brawley Seismic Zone (BSZ) comprise the principal transfer zone accommodating strain between the San Andreas and Imperial faults in southernmost California (Figure 1). The BFZ is a complex north-south trending set of discontinuous fault scarps (*e.g.*, Figure 2) that mark the eastern boundary of Mesquite Basin, in part a transtensional graben that is bounded on the west by the northwest trending Imperial fault. The BSZ is a diffuse zone of seismicity that extends north-northwest from the BFZ toward the San Andreas fault (SAF) at Bombay Beach; focal mechanisms and seismicity lineaments within the BSZ indicate that most of the earthquakes occur on left-lateral northeast trending and right-lateral northwest trending cross-faults (*e.g.*, Fuis *et al*., 1982; Nicholson *et al*., 1986; P. Shearer, unpub. data). The relationship between the BFZ and the BSZ, both at the surface and at depth, is poorly understood.

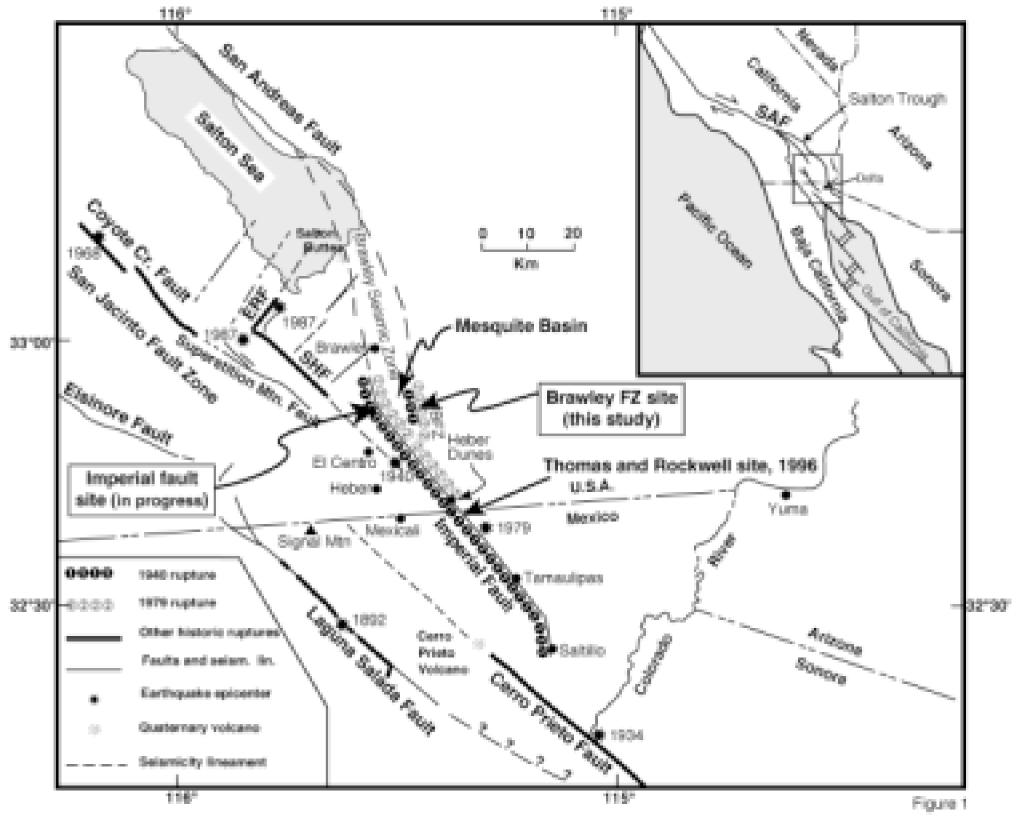

Figure 1. Generalized fault map of the southern part of the Salton Trough. Surface ruptures indicated for the 1892 ($M\ 7^1/_4$), 1934 (M_L 7.1), 1940 (M_W 6.9), 1968 (M_W 6.5), 1979 (M_W 6.4), and 1987 (M_W 6.2 and 6.6) earthquakes. ERF: Elmore Ranch fault; SHF: Superstition Hills fault.

Although field observations revealed that minor surface faulting occurred along several kilometers of the BFZ during the 1940 M_W 6.9 Imperial Valley earthquake (A. E. Sedgwick, unpub. data, 1940; Sharp, 1982b), the surface expression of this fault zone was generally unrecognized until new faulting occurred during a swarm of small earthquakes in 1975 (Johnson and Hadley, 1976; Sharp, 1976, 1977). The BFZ ruptured again along with the Imperial fault in the 1979 M_W 6.4 earthquake, and faulting along the BFZ in 1979 was more extensive than faulting documented in any of the prior historical earthquakes. [Indeed, prior to 1979, most authors referred to the BFZ as simply the "Brawley fault," but the number and distribution of 1979 surface ruptures led Sharp *et al*. (1982) to employ the term "Brawley fault zone" instead.] Slip along the BFZ does not appear to have exceeded several decimeters in any of the historical events. Despite the modern difficulty of locating fault traces within the BFZ because of ground modification for agricultural purposes, inspection of U.S. Department of Agriculture [USDA] aerial photos from 1937, when much of the

Figure 2. Portion of a topographic map showing the 1979 rupture of the BFZ. From Sharp *et al.* (1982).

BFZ was in a more natural state, reveals that most of the historical ruptures followed clearly identifiable pre-existing faults or lineaments within the limits of uncertainty, typically ±5 m (Sharp, 1977, 1982b; Sharp *et al.*, 1982). In addition to the historical coseismic ruptures just discussed, aseismic creep and triggered slip have been documented along the BFZ episodically since about 1960 (*e.g.*, Sharp, 1976; Sharp and Lienkaemper, 1982; Louie *et al.*, 1985). In 1975, a creepmeter was installed across the BFZ at Harris Road (see Figure 2 for location), but problems with the creepmeter have made interpretation of its record difficult (Goulty *et al.*, 1978; Cohn *et al.*, 1982; Louie *et al.*, 1985); the creepmeter was abandoned in the late 1980s.

Our work involved an attempt to better understand the long-term behavior of the BFZ. Unfortunately, the surface trace of the entire known BFZ has been extensively modified or destroyed for agricultural or cultural purposes. Fields, typically quarter-mile squares or larger, have been leveled to facilitate their irrigation, which resulted in the removal or redistribution of considerable volumes of earth, especially from the higher side of any topographic step that lay within the boundaries of a parcel of land. This process has effectively removed 1–2 m of important section, stratigraphy and history from the upthrown side of any fault strand. Tilling of these fields with heavy machinery has disturbed the sediments and destroyed evidence of prehistoric faulting even deeper into the section. The roadways generally predate the agricultural leveling, so that the fault is generally best preserved along the dirt shoulders of the few paved roads that cross the fault. However, examination of all roads that cross the BFZ revealed problems with most of the sites: narrow shoulders in most places and buried utility cables along Worthington Road (see Figure 2) made the south shoulder of Harris Road the only location along the known BFZ where it was feasible to dig a trench. Nonetheless, much of the south shoulder of Harris Road had been dug up previously for the installation and routine servicing of the creepmeter, so only a small part of the shoulder within the fault zone was not completely destroyed. Furthermore, even at the Harris Road site, the ~3 m cumulative scarp has been graded significantly to allow vehicles to drive over the scarp at high speeds. None of the dirt shoulders (along any road) are wide enough to permit 3-dimensional trenching, and there are no preserved fault-crossing features (such as stream channels) anywhere along the known BFZ that would make 3-D trenching useful; this specifically precludes any possibility of constraining the amount of lateral slip in recent events. Consequently, the observations and conclusions that we were able to make at this site are very limited and leave many questions unanswered, but they appear to be the most definitive paleoseismic observations and conclusions that can be made anywhere along the BFZ at the present time.

THE BRAWLEY FAULT ZONE AT HARRIS ROAD

Unlike the Imperial fault to the west, most of which is either a single fracture or a fairly organized set of continuous *en echelon* fractures, the BFZ is a complex, disjointed set of fractures that collectively define a zone of faulting up to a kilometer wide (*e.g.*, Figure 2; see also Sharp *et al.*, 1982, plate 1). At Harris Road, at least three strands of the BFZ cross the pavement (Figures 2–3): two strands ~21 m apart which lie to the west, and a third strand ~400 m farther east. For convenience, we will hereinafter refer to these three strands, from west to east respectively, as faults F1w, F1e, and F2; likewise, we will refer to the area of the south shoulder of Harris Road around strands F1w and F1e as Site BFH1, and we will refer to the area of the south shoulder around strand F2 as Site BFH2 (see Figure 3). In 1975, only fault F1w broke (Sharp, 1977); strands F1e and F2 were not identified until they slipped in 1979 (Sharp *et al.*, 1982). The exact locations of our investigations on each fault strand are given in Table 1.

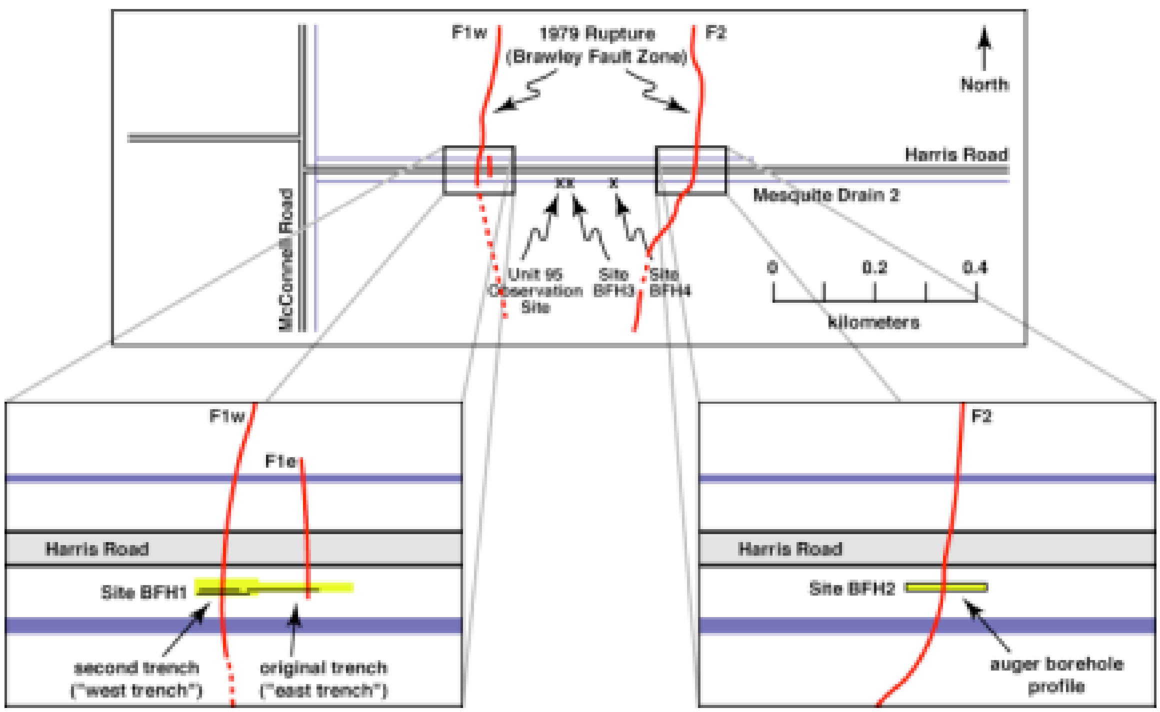

Figure 3. Map of the sites along Harris Road discussed in this paper.

In addition to the three fault strands known prior to our study to cross Harris Road, we considered the possibility that there may be additional strands at this location. It is possible that historical ruptures have not revealed all strands of the BFZ, especially in light of the observation that not every strand ruptures in every earthquake. Similarly, because Sharp (1977) could not identify every Holocene trace of the BFZ based on lineaments in 1937 aerial photos, we cannot rely on his work to guarantee that we have recognized all strands. Fortunately, most of the section is already

Table 1: Site Locations

Site (see Fig. 3)	Fault Strand (see Fig. 3)	Latitude-Longitude (NAD-27) Latitude (° N)	Latitude-Longitude (NAD-27) Longitude (° W)	UTM Zone 11 (NAD-27) Northing (m)	UTM Zone 11 (NAD-27) Easting (m)
BFH1w	F1w	32.8828	115.4794	3639134	642248
BFH1e	F1e	32.8828	115.4791	3639134	642269
BFH2	F2	32.8828	115.4748	3639139	642674

exposed in an east-west transect that spans the width of the BFZ in the vicinity of Harris Road. Parallel to and immediately south of the south shoulder of Harris Road is Mesquite Drain 2 (see Figure 3), a ~4 m deep agricultural drainage canal with sloped earthen walls. The exposure extends from near McConnell Road, ~300 m west of F1w, to a point ~900 m east of F2. For perhaps 70% of this exposure, crude stratigraphy and faults are exposed in the walls of the drain (*e.g.*, Figure 4); in the remaining part of the drain, either the original stratigraphy has been replaced by fill, or it is covered by dense vegetation.

The three faults that ruptured in 1979 (F1w, F1e, and F2) are clearly evident on the drain walls: stratigraphic beds that can be followed for tens of meters or more are tilted near each of the three faults and are abruptly truncated at the faults (see Figure 4 a–d). An inspection of the remaining unobscured section in the drain walls revealed nothing else comparable to these three faults, although a fourth and a possible fifth fault strand—both of which appear to be less significant than F1w, F1e, and F2—were discovered (see Figure 4 e–h); they will hereinafter be called F3 and F4, respectively. Additional faults (some perhaps significant) may be present in any of the areas of the drain where the original stratigraphy is obscured, although there is no evidence to suggest we are missing a significant amount of vertical displacement.

In 1940, rupture along the (then unknown) BFZ was not well documented; in his unpublished field notes, A. E. Sedgwick described, in only general terms, a 3-km-long surface rupture in the vicinity of Harris and Ralph Roads that trended north-south and bounded the relatively downdropped basin of Mesquite Lake (Sharp, 1982b); an independent observation of displacement at Keystone Road (Sharp, 1976, 1982b) suggests that rupturing along the BFZ broke the surface for at least 5 km from north to south and that more than one strand was involved. Although it is probably safe to assume from A. E. Sedgwick's description that at least one strand crossing Harris Road ruptured in the 1940 earthquake, we have too little information to postulate which of the strands were involved.

SLIP AT HARRIS ROAD, 1940–1979

A temporally and spatially complex history of aseismic creep, coseismic slip, and postseismic deformation has been documented in the BFZ since the 18 May 1940 Imperial Valley earthquake, although the quality and quantity of the documentation has varied tremendously in those 63 years. Specifically, very little is known about creep prior to August 1970. Below is a summary of the observations of or inferences about creep and slip across the BFZ at Harris Road since 1940; the amount of movement documented during that time should only be construed as a minimum, even since 1970. This information is presented more succinctly in Table 2.

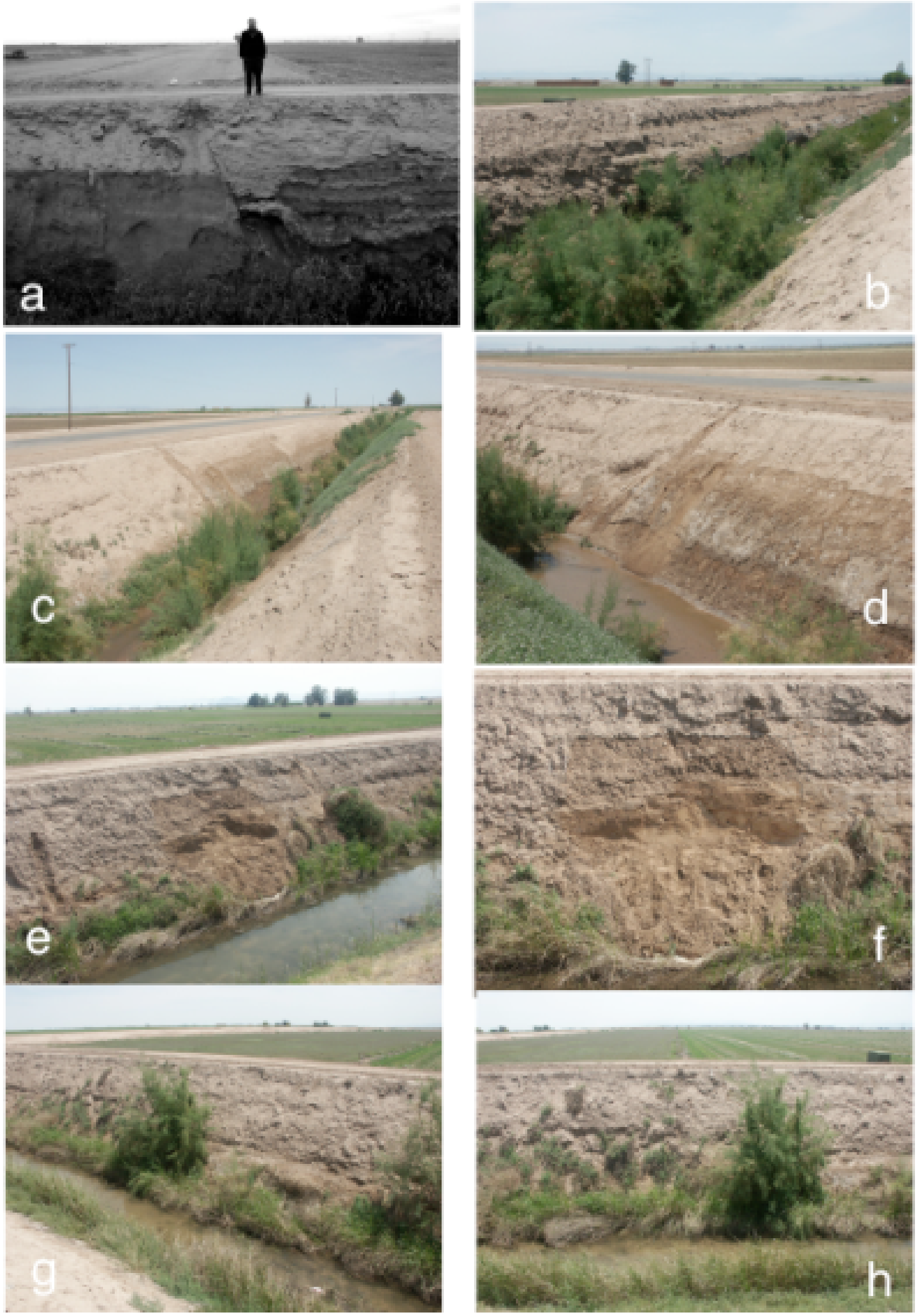

Figure 4. Photos of fault strands in walls of Mesquite Drain 2: (a) fault F1e, looking to the south; (b) F1w, looking to the southwest; (c) F2, looking to the northeast; (d) F2, looking to the northwest; (e) F3, looking to the southwest; (f) F3, looking to the south; (g) F4, looking to the southeast; and (h) F4, looking to the south.

Table 2: Summary of BFZ Historical Creep at Harris Road

Time Window	Fault Strand F1w	F1e	F2	References *
May 1940 earthquake	probable displacement; details unknown			
after 1940 earthquake; prior to Aug 1970 paving of Harris Road	probable displacement; details unknown			
Aug 1970 to 5 Feb 1975	8 cm ESU ~0 cm RL	~0 cm	~0 cm	1
5 Feb 1975 to 25 Oct 1977	0	0	0	1, 2
25 Oct 1977 to 17 Jan 1979	~0.8 cm ESU ~0 cm RL	~0.1 cm ESU ~0 cm RL	~0 cm	2
17 Jan to 19 Apr 1979	0	0	0	2
19 Apr to 17 Oct 1979 (presumed to be primarily coseismic slip)	5.1 cm ESU 7.3 cm RL	2.5 cm ESU ~0 cm RL	~7 cm ESU ~0 cm RL	2, 3
17 Oct to 30 Dec 1979	~0 cm	~0 cm	~0 cm	2
30 Dec 1979 to 6 Jan 1981	amount of slip unknown			
6 Jan to 30 Apr 1981	~0 cm	~0 cm	~0 cm	4
30 Apr 1981 to 12 Feb 1984	amount of slip unknown			
12 Feb 1984 to 13 Apr 1988	~0 cm	~0 cm	~0 cm	5, 6
13 Apr 1988 to ~ 16 Oct 1999	amount of slip unknown			
~ 16 Oct to 10 Nov 1999	~0 cm	~0 cm	~0 cm	7
10 Nov 1999 to 1 Apr 2002	amount of slip unknown			
1 Apr 2002 to 2 Nov 2002	no obvious creep observed			8
2 Nov 2002 to 14 Dec 2002	~0.6 cm ESU ~0.4 cm RL	~0 cm	~0 cm	8
14 Dec 2002 to 24 Apr 2004	no obvious creep observed			8

* References:

1. Sharp (1976)
2. Sharp and Lienkaemper (1982)
3. Sharp *et al.* (1982)
4. Sharp *et al.* (1986)
5. Sharp (1989)
6. McGill *et al.* (1989)
7. Rymer *et al.* (2002)
8. This work

- At least 5 km of the BFZ, from Ralph Road to Keystone Road, ruptured along with the Imperial fault in the 1940 earthquake. Although at least one of the strands crossing Harris Road apparently was involved, details of the rupture and of offsets were not documented (Sharp, 1982b). Recollections by local resident Mr. Richard Hansen (later a superintendent of roads with the Imperial County Department of Public Works) suggest that an abrupt east-side-up (ESU) scarp, perhaps 10 cm high, formed across the then-unpaved Keystone Road, 3.6 km north of Harris Road (Sharp, 1976); this is comparable to the displacement at Keystone Road in 1979.
- Additional ESU uplift across Keystone Road after 1940 but before 1960 was noticed by a local rancher and pointed out to the county Department of Public Works prior to the regrading and paving of Keystone Road in 1960 or 1961 (Sharp, 1976). Nothing is known about slip at Harris Road during this period, but presumably creep occurred there as well.
- Surface ruptures formed along a 10.4-km long segment of the BFZ during an earthquake swarm in late January and early February 1975; most of the displacement occurred at about the time of the largest shock (M_L 4.8), on 23 January (Sharp, 1976). A scarp height of 8 cm (ESU) was measured on 5 February 1975 by leveling across F1w on Harris Road, but the pre-swarm elevation profile of the road is unknown, so the scarp height indicates only the total slip since August 1970, when Harris Road was regraded and paved (Sharp, 1976). No horizontal component of slip was observed at any location along the fault in 1975 (Sharp, 1976).
- The BFZ appeared fairly quiescent from March 1975 to April 1979 except for one small displacement at Harris Road that occurred between October 1977 and January 1979. Between October 1977 and January 1979, a vertical step-like displacement of ~0.8 cm (ESU) occurred at F1w (Sharp and Lienkaemper, 1982). Leveling data over that time interval also show a subtle step in the road surface across F1e, although cracking was never detected there before the 1979 earthquake; the leveling data indicate that the post-1979 small scarp at F1e was almost entirely due to the 1979 event (Sharp and Lienkaemper, 1982; Sharp, 1982b). Fault F2 was not yet known, so there could not have been appreciable movement across F2 from October 1977 to January 1979 (or for that matter, from August 1970 to April 1979).
- Cumulative offsets at Harris Road between successive leveling measurements on 19 April 1979 and 17 October 1979—a time period which included the 15 October 1979 mainshock—were determined from the ongoing leveling measurements and from an offset concrete irrigation canal. Reported offsets were: 5.1 cm ESU and 7.3 cm right-lateral (RL) across F1w; 2.5 cm ESU and negligible RL across F1e; and ~7 cm ESU and negligible RL across F2 (Sharp *et al.*, 1982; Sharp and Lienkaemper, 1982). The creepmeter across fault F1w at Harris Road indicated that the coseismic and immediate postseismic displacement grew to its full dimension over more than 12 hours (Cohn *et al.*, 1982). Most of the displacement is assumed to have occurred coseismically and/or in the 12–hour period following the earthquake, but unequivocal evidence precluding slip between 19 April and the 15 October mainshock is lacking. [Records from the Harris Road creepmeter are difficult to interpret for at least two reasons: (1) dextral slip would reduce the distance between piers while subsidence to the west of the fault would increase it, owing to the "backwards" orientation of the Harris Road creepmeter; and (2) vertical motion would be recorded at very low gain, owing to the near-90° angle between the fault and the wire for the vertical component of slip (Cohn *et al.*, 1982; Louie *et al.*, 1985). Consequently, vertical slip cannot be distinguished from lateral slip on the creepmeter recordings, and a creep event with a predominantly (or exclusively) dip component of slip might not be resolvable on the creepmeter. Thus, it appears that available data cannot further constrain the timing of the April to October 1979 slip.] At Keystone Road, the offset across the single strand was determined to be ~9.5 cm vertical (ESU) and 7.3 cm RL (Sharp *et al.*, 1982; Sharp and Lienkaemper, 1982).

- Following the 15 October 1979 mainshock, minor postseismic westward tilting of the ground surface without vertical movement at the fault traces was recorded; by 30 December 1979, the east end of the leveling line across F1w and F1e had risen ~1 cm with respect to the west end. However, the large amount of afterslip that was observed on the Imperial fault following the 1979 earthquake (in many cases, the amount of afterslip approximately equaled the amount of coseismic slip) generally was not observed on the BFZ (Sharp and Lienkaemper, 1982).

SLIP AT HARRIS ROAD, 1980–1999

- After 1979, additional leveling profiles were surveyed, but data for only selected time intervals have been published, and regrettably, a thorough search by the primary author (A.J.M.) and M.J. Rymer through the records of R.V. Sharp did not bring to light any additional useable data. The only time intervals for which the vertical slip history of the BFZ at Harris Road is known cover a brief period in early 1981 and a continuous period from February 1984 to April 1988. No shallow slip apparently occurred across any of the surface traces of the BFZ at Harris Road during those intervals, but broad tilting of the profiles that is consistent with deep slip was observed (*e.g.*, Sharp, 1989). Additional details are presented in Table 2.
- In addition to the leveling profile re-surveys, the BFZ was inspected for triggered slip following a number of significant earthquakes in southern California in the 1980s and 1990s, but no clear evidence of such slip was ever found (*e.g.*, Sharp *et al.*, 1986; Sharp, 1989; McGill *et al.*, 1989; Rymer *et al.*, 2002).

A CREEP EVENT AT HARRIS ROAD IN 2002

Although regular monitoring of creep was largely discontinued by 1988, it is evident that creep still occurs along the BFZ more than two decades after the 1979 earthquake. Over time, cracks in paved roads and concrete irrigation canals (some with measurable displacement) have grown and widened, and in November 2002, a localized strain event developed along the BFZ while our trench was open. The exact timing of the event and the geographic extent of creep are not well constrained, but the event produced ~6 mm of vertical (ESU) and ~4 mm of RL displacement across fault F1w, cleanly offsetting the etched walls of the trench on the south shoulder of Harris Road. No other creep was observed in the nine months that trenches were open at this site.

That creep had occurred at the trench site (BFH1) was first recognized when one of the authors (A.J.M.) and a field assistant (D. M. Verdugo, San Diego State University) arrived at the site on the afternoon of 21 November 2002, after being away from the trench for three weeks. The trench had already been open for several months, and the walls of the trench had been flattened, etched, photographed, and logged during previous visits. That day, a fresh crack was plainly visible in the walls of the trench, and it cleanly cut across the spoils pile adjacent to the trench. The crack continued on the ground surface for tens of meters in either direction from the trench, following the fault trace, until it went into agricultural fields; there, any evidence of movement would have been difficult or impossible to recognize, owing to the dense crops growing in the fields.

On the ground surface, the crack appeared to be characterized primarily by extension of several millimeters; if there was any displacement at the ground surface, it was masked by the tensile opening. At the base of the trench, 2 m below the ground surface, the crack was also dominated by extension; however, given the smooth, planar nature of the flattened trench walls prior to the creep event, A.J.M. and D.M.V. were able to resolve 1-2 mm of RL slip at the base of the trench, with that value generally decreasing to less than a resolvable threshold as the cracks rose to the ground surface. If there was any dip component of slip, it was also below resolution.

In the trench faces that had already been logged, the fresh crack generally followed a preexisting fault, but the fresh crack extended higher up in the section than we were able to confidently log the fault previously. As a caveat, the uppermost part of the section is artificial fill, and it is not clear whether a fault would have been recognizable in that material if it had moved prior to the opening of the trench. Unfortunately, light ran out on 21 November before other sites in the

BFZ could be inspected for creep, and none of us were able to return to the site until 13 December 2002.

We constrain the timing of the onset of slip to being prior to our arrival that day and subsequent to our departure on the previous occasion. These constraints require that the slip event initiated between approximately 16:00 PST on 2 November 2002 (00:00 GMT on 3 November 2002) and 13:30 PST (21:30 GMT) on 21 November 2002. We searched the Southern California Seismic Network (SCSN) earthquake catalog (available at http://www.data.scec.org/research.html) for earthquakes on or near the BFZ or within 20 km of the trench site between 00:00 GMT on 20 October and 00:00 GMT on 22 November 2002. (Note that results of this search would include events up to two weeks prior to the earliest possible onset of creep at Site BFH1, which might be relevant if the creep was a delayed response to coseismic slip at depth.) As it turns out, no events in the catalog fit those criteria, so it appears that this creep event is not associated with any local earthquakes.

When A.J.M., T.K.R., and D.M.V. returned to the trench on 13 December 2002, it was apparent that additional creep had taken place since our prior visit, as the cracks in the trench were wider, and the displacement across them was greater. On 13 December, using the most reliable piercing points we could find, we estimated that a total of ~6 mm of vertical (ESU) displacement and ~4 mm of RL displacement, in addition to several mm of extension, had occurred across F1w in the lower wall of the trench. As was the case in November, the amount of slip appeared to diminish upward, although an alternate explanation could be that in the uppermost meter or two, the deformation was more diffuse, so that it wouldn't be recognized as discrete slip along a fault surface. We measured a total of ~8 mm of ESU vertical displacement across the road surface in the middle of Harris Road, but the road surface was not completely level prior to November. Hence, the ~8 mm displacement reflects only the total vertical displacement since the road was last patched. (An inquiry in 2004 to Mr. Manuel Provencio, a superintendent of roads with the Imperial County Department of Public Works, reveals that although no records are kept of when specific roads are patched, the crack on Harris Road at F1w has typically been re-patched in winter, once every year or two, at least in recent years. This suggests that additional undocumented creep has occurred at the site repeatedly since 1988.)

On the morning of 14 December, several other sites were inspected for creep. Cracks were observed at Keystone Road and along McConnell Road, 1 km south of Keystone Road, in the same locations as where faulting was observed in the 1979 earthquake (Figure 2; Sharp *et al.*, 1982, plate 1). At these locations, cracks in the pavement (which likely represented the cumulative effect of years of slip) marked the locations of the fault strands; somewhat obscured but nonetheless visible cracks on the adjacent dirt shoulders (which likely were not more than a month or two old) indicated the relative recency of renewed creep. No clear evidence of fresh creep could be found north of Keystone Road; a search was not performed south of Harris Road. Along Harris Road, no evidence for creep was observed along F1e in either November or December, and no evidence was observed along F2, F3, or F4, although the latter faults were not checked in November, and any evidence of creep could have been destroyed by 14 December.

In regard to the timing of the event, one important observation is that, based on the judgment of A.J.M. and D.M.V., the cracks appeared fresh on 21 November 2002; in contrast, when the two returned to the site on 13 December 2002, the cracks were considerably degraded and in some cases no longer visible. This marked contrast might suggest that the cracks formed very shortly (*i.e.*, within a few days) prior to 21 November. However, the degradation of the cracks probably has more to do with the weather during that time than with the duration for which the cracks were exposed. Examination of weather records from the National Climatic Data Center (NCDC) (available at http://www.ncdc.noaa.gov/) reveals that the only measurable precipitation that occurred between 1 November and 15 December 2002 in any of the nearby towns of Brawley, Imperial, El Centro, or Calexico occurred entirely within a 5-day window between 17:00 PST on 25 November and 09:00 PST on 30 November—after the 21 November visit but prior to the 13 December visit; the rainfall totals at each site during that period were 4.3, 4.6, 6.6, and 4.6 mm, respectively.

The search of the SCSN earthquake catalog was extended through 00:00 GMT on 14 December 2002, to check if the additional creep (subsequent to 21 November) could be attributed to any earthquakes. Four events appear in the catalog that occurred within 20 km of Site BFH1 (see Table 3), but none of them were particularly close to the BFZ, none were larger than *M* 2.5, and all four events occurred *after* the rain event of 25–30 November and within 10 days of the 13 December visit, which would be inconsistent with the uniformly degraded appearance of the cracks by 13–14 December 2002. Hence, we once again argue that the creep was completely aseismic and not associated with any local earthquakes.

Table 3: Earthquakes within 20 km of BFH1, Oct–Nov 2002

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List of network-located earthquakes within 30 km of the Trench Site,
spanning the time period in which the creep event may have occurred

Search  Parameters:

 Start Date:     2002/10/20 00:00:00 (UTC)   [2002/10/19 16:00:00 PST]
 End Date:       2002/12/14 00:00:00 (UTC)   [2002/12/13 16:00:00 PST]
 Minimum Mag:    0.0
 Minimum Depth:  0.0
 Location:       within a 20 km radius of 32.8828 N, 115.4794 W
 Catalog:        TriNet (SCSN)

Mag Date          Time       Latitude   Longitude   Dpth   Location
--------------------------------------------------------------------------------
1.5 2002/12/04 14:47:34 33 01.5 N 115 33.4 W  5.5  6 km ESE of Westmorland, CA
1.7 2002/12/08 05:41:50 32 43.7 N 115 29.0 W 15.7  7 km N   of Calexico, CA
1.3 2002/12/09 21:51:31 32 46.2 N 115 26.0 W 10.0 11 km ESE of El Centro, CA
2.5 2002/12/12 17:23:27 32 58.2 N 115 31.6 W 15.9  1 km NE  of Brawley, CA

Date and Time in UTC;  Latitude and Longitude in degrees/minutes;  Depth in km

Information  Sources:
   Southern California Seismic Network (SCSN) / TriNet Earthquake Catalog
        http://www.data.scec.org/catalog_search/
        http://www.data.scec.org/catalog_search/radius_index_develop.html
        http://www.data.scec.org/catalog_search/catalog_search_help.html

Date of Catalog Search:  2 May 2004
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PALEOSEISMIC INVESTIGATION: EVIDENCE FOR LATE HOLOCENE SLIP

Initially, a single trench was excavated across fault strands F1w and F1e parallel to Harris Road, on the south shoulder of the road. In the vicinity of F1w, the trench was ~3 m deep, but it shallowed westward. Unfortunately, because of the presence of water-saturated loose sands underlying more cohesive units near F1w, the trench began collapsing in the vicinity of F1w within minutes of excavating that part of the trench, despite the fact that we had already emplaced hydraulic shores for support. Because of continued but irregular irrigation of nearby fields, the level of the water table fluctuated but was consistently shallower than the base of the trench at its deeper end, near F1w; consequently, we were never able to stabilize that part of the trench long enough to clean, photograph, and log the area around F1w. Instead, we focused on logging the stable part of the trench (the area east of F1w, including the area around F1e); we then backfilled the first trench and excavated a new, shallower, wider benched trench in the vicinity of F1w. Because the first trench focused on F1e, we will refer to that trench as trench BFH1 East; the second trench, which focused on F1w, will be referred to as trench BFH1 West (see Figure 3).

In BFH1 East, because of complete redundancy of information, only the south wall was logged; in BFH1 West, because the north wall of the trench within the fault zone was almost entirely disrupted from excavations related to the installation and servicing of the creepmeter, once again only the south wall was logged. In both trenches, the trench faces were gridded, etched, and photographed prior to being logged; the photographs were rectified to the grid and mosaicked together, and field logging was done directly on the rectified mosaicked photographs. The drafted logs are shown in Figures 5–6.

The initial chronologic sequence of stratigraphic units was established based on the principle of superposition and the sense of slip of each strand of the BFZ known from historical observations. The age of each unit was constrained by the results of ^{14}C analysis using accelerator mass spectrometry (AMS) techniques on individual pieces of detrital charcoal from various strata, by optically stimulated luminescence (OSL) dating of two sandy units, and by consideration of oral traditions by the native Cahuilla people (Modesto and Mount, 1980) and historical accounts by Spanish explorers (Sieh and Williams, 1990) that preclude a significant lake in the Salton Trough at any time more recent than the early 18th century.

A brief discussion is warranted on the nature of radiocarbon analysis of detrital charcoal in the Imperial Valley. Due to the aridity of the pre-agricultural Imperial Valley, local natural fires were unlikely, as the vegetation was widely spread and it would have been very difficult to initiate a range fire under these conditions. There are two possible sources of charcoal in the vicinity of the BFZ site: range and forest fires in the various drainage headlands surrounding the Imperial Valley or on the Colorado Plateau, and fires by the indigenous people of the area, the Cahuilla Indians. Both sources have potential for a large inherited age. In that (*a*) ^{14}C dates on detrital charcoal record the date of wood growth, (*b*) the burning of green wood is not as likely as that of old, aged wood, and (*c*) there may be considerable delay between the burning of a range or forest and the subsequent transport of a piece of charcoal to its ultimate deposition site, the majority of burned wood will likely have substantially older apparent ages than the actual age of the host sediment. In addition, in the case of cooking fires prepared by the indigenous people, one would expect that the Cahuilla Indians would be more likely to choose older wood to burn. Therefore, a detrital charcoal sample provides only a maximum age constraint.

In addition to the trenches at Site BFH1, a series of auger boreholes were dug across fault F2 at Site BFH2 (see Figures 3 and 7). Like the trenches farther west, the boreholes served to constrain the amount of vertical displacement across the fault; however, in this case, because we anticipated that the uppermost part of the section had been removed, and because we would not be able to determine an event chronology for the part of the section that was missing, we realized that the limited data available at Site BFH2 did not justify the time, effort, or cost necessary to excavate a trench and to log it in detail. The data obtained from the boreholes, which will be presented in this paper, provide adequate constraints on the amount of vertical slip at this site.

Finally, fault F3 was examined by cleaning off its exposure in the south wall of Mesquite Drain 2; this site will be referred to as Site BFH3 and will be discussed later in this paper. Fault F4 was not examined in detail, and it will be discussed only briefly.

REGIONAL STRATIGRAPHIC SETTING

Regionally, for the past millennium and presumably longer, sedimentation in the Imperial Valley has been cyclic and dominated by the Colorado River. During mid-Pleistocene time, the Colorado River built a delta across the Salton Trough from an apex near Yuma, Arizona (Figure 1; Van de Kamp, 1973). At least five times during the past 1200 years, the Colorado River has switched from its present course (emptying southward into the Gulf of California) to flowing northward into the Salton Trough. Each time the Colorado River followed a northward course, it inundated much of the below-sea-level Coachella and Imperial Valleys, producing the freshwater Lake Cahuilla that typically rose to elevations of between 9 and 13 m above modern sea level, the altitude of the lowest point on the Colorado River delta (Stanley, 1963, 1966; Thomas, 1963; Van de Kamp, 1973; Waters, 1983; Sieh, 1986; Sieh and Williams, 1990; Rockwell and Sieh, 1994;

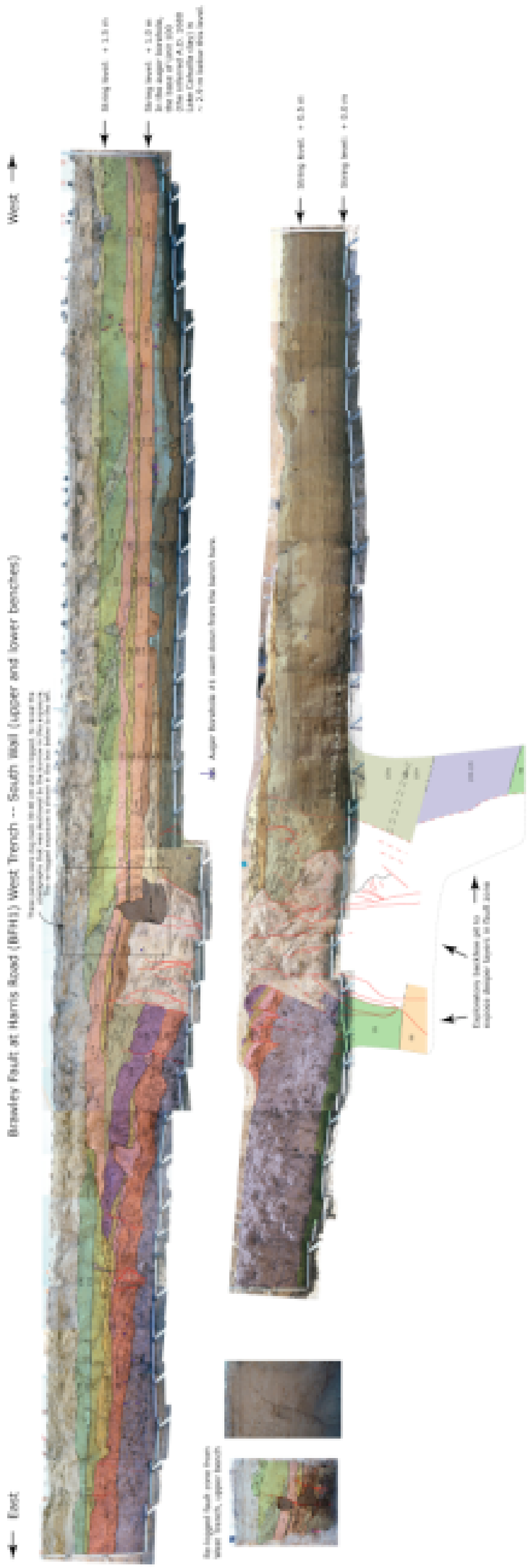

Figure 5. Log of the south wall of trench BFH1 West. Units numbered 200 and above are inferred to be modern anthropogenic fill. Carbon-14 sample sites are denoted by open circles. Also shown is a log of a second exposure of the F1w fault zone, ~40 cm south of the main exposure. The deepest part of the exposure, shown without a photomosaic background, could not be logged in detail; on the last day that the trench was open, a backhoe was used to deepen the trench, in order to expose as much section as possible. After the deeper section was exposed, there was only enough time to sketch the main contacts before that part of the trench collapsed. Prior to the deepening of the trench, however, an auger borehole was dug into the floor of the trench, in order to accurately measure the depths to key contacts on the downthrown side of F1w. From the combination of these depth measurements and the sketch we were able to make on the last day, we feel confident that the information shown on the deeper portion of the log is correct, although we recognize that some details were probably missed.

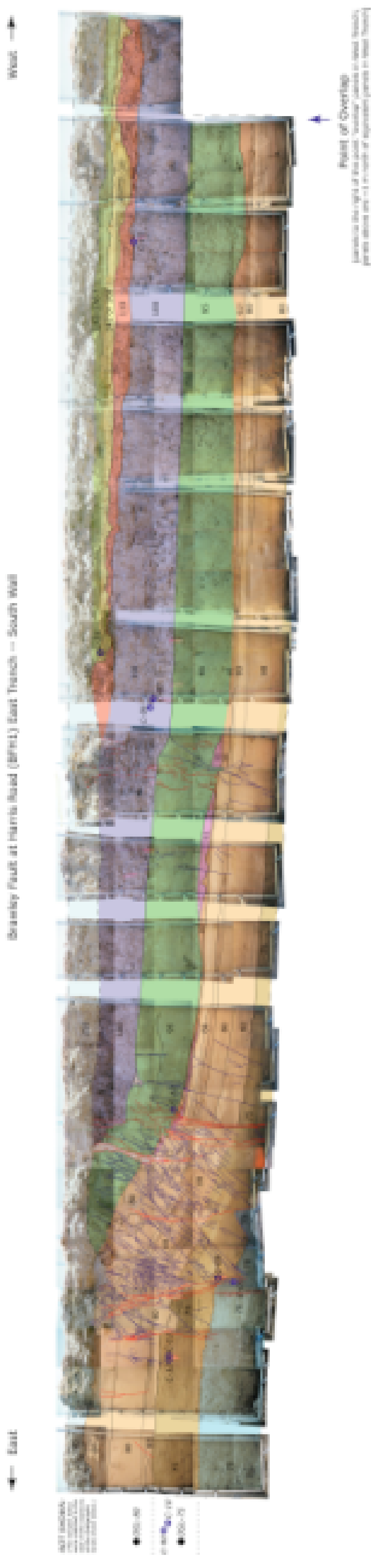

Figure 6. Log of the south wall of trench BFH1 East. Units numbered 200 and above are inferred to be modern anthropogenic fill. Carbon-14 sample sites are denoted by open circles; the two OSL sample locations are designated by filled black circles.

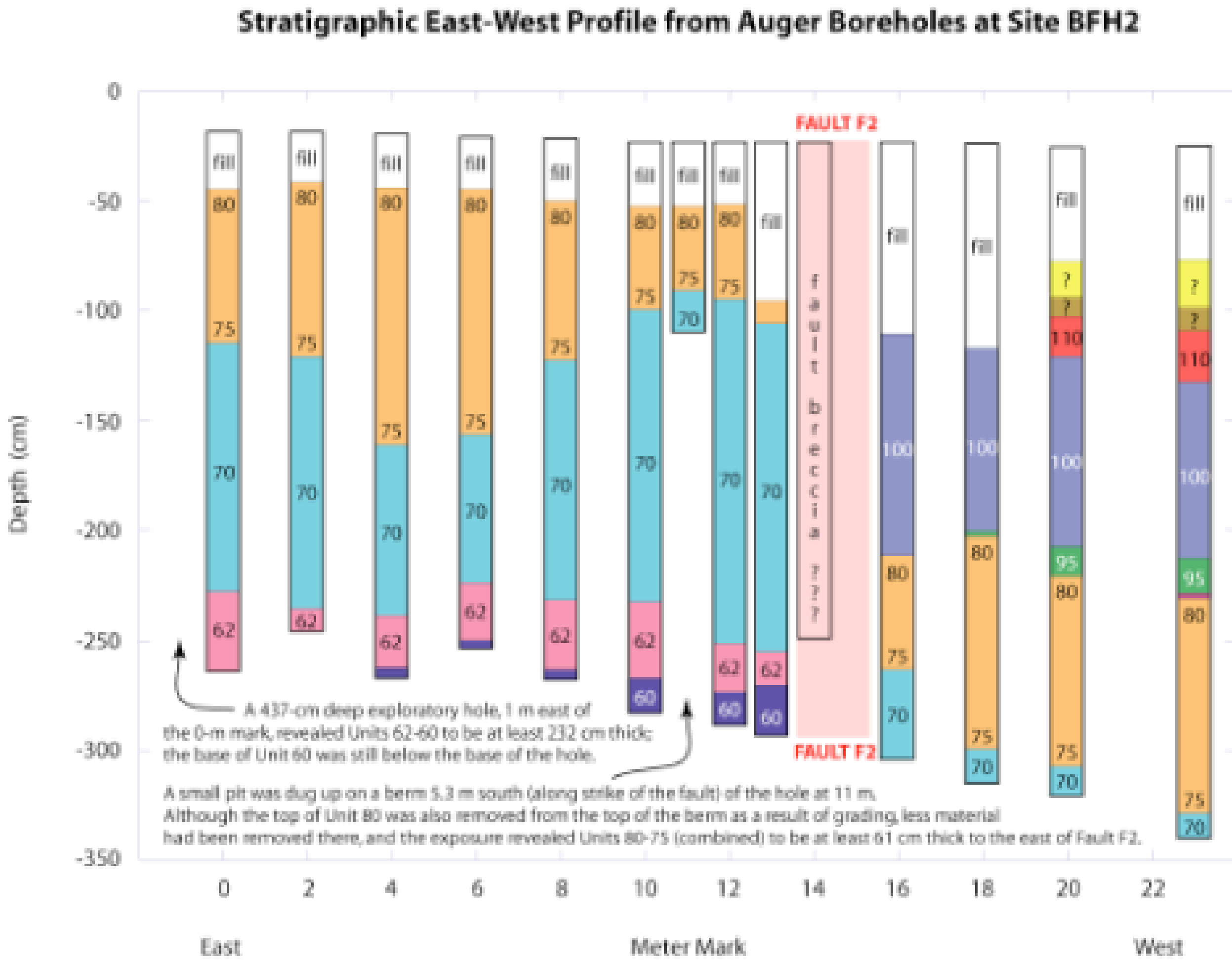

Figure 7. Stratigraphic profile across fault F2 at Harris Road inferred from auger boreholes at Site BFH2.

Gurrola and Rockwell, 1996; Thomas and Rockwell, 1996; Orgil, 2001). After filling to an elevation of 13 m, excess input to the lake flowed south over the delta to the Gulf of California; eventually, the Colorado River would revert to a southward course, and due to the hot, dry climate, Lake Cahuilla would desiccate over about 60–70 years (Sieh and Williams, 1990).

While five Lake Cahuilla highstands have been recognized in the past 1200 years at various sites along the shoreline, it is possible that the lake never desiccated completely between highstands; it is also possible that there were additional partial fillings of the lake in which the Colorado River did not flow northward for long enough to fill the lake entirely. During the early 20th century, attempts to divert part of the Colorado River into the Imperial Valley for agricultural purposes resulted in the Colorado River flowing uncontrolled into the Salton Trough from 1905 to 1907. The Salton Sea, as it was then called, reached a maximum elevation of 60.2 m below sea level in February 1907 (Cory, 1913, p. 1412; Sykes, 1937, Figure 62) before it was brought under control, and it remains at about –70 m today.

Historical evidence (Sieh and Williams, 1990) and oral traditions by the native Cahuilla (Modesto and Mount, 1980) preclude the possibility of a Lake Cahuilla highstand at any time since ca. A.D. 1680. Although the sparse early historical data might permit a short-lived *partial* filling of Lake Cahuilla between ca. 1680 and ca. 1825, there is no known historical or geologic evidence of any lakes larger than the present Salton Sea since the A.D. 1680 lake, and historical observations preclude any such lake at any time since at least ca. A.D. 1825 (Emory, 1848; Blake, 1854, 1915;

Barrows, 1900; Cory, 1913, p. 1228). In particular, from descriptions by Barrows (1900), Blake (1915), and Cory (1913, p. 1228) of consistently small bodies of water, and from the fact that no flood appears to have lasted more than one season or year (in contrast to the two-year flood from February 1905 to February 1907 that produced the Salton Sea), we infer that all of the short-lived 19th century lakes were smaller than the 20th century Salton Sea.

In addition to the Salton Sea and previous partial fillings of the Salton Basin, several smaller lakes have periodically filled closed depressions elsewhere in the Imperial Valley, within the broader footprint of Lake Cahuilla. One such basin is Mesquite Basin (Figures 1, 8). Modern USGS topographic maps show the –140-foot (–42.7-m) elevation contour within Mesquite Basin as a 3.5-km (north to south) by 2.5-km (east to west) closed depression, whereas the higher –135-foot (–41.1-m) contour opens to the north. U.S. Geological Survey (1908) shows a lake (Mesquite Lake) filling Mesquite Basin in 1908: this lake covered an area slightly larger than the –140-foot contour, being roughly 4.25 km north to south by 3.0 km east to west.

Sub-aqueous deposits that have typically been associated with Lake Cahuilla range from deltaic sands to lacustrine clays. Deltaic deposits may originate from the Colorado River, or they may have a more local source if a large storm that caused significant runoff along the basin margins occurred while Lake Cahuilla was stationary at a particular level. Lacustrine deposits may also originate locally or from the Colorado River and represent deeper water settling of suspended load. Other deposits in the Imperial Valley include meandering channel deposits (relatively low stream gradient); alluvial fans and braided-stream deposits (relatively high stream gradient); barrier beaches; and aeolian sand deposits (Van de Kamp, 1973).

TRENCH STRATIGRAPHY

The BFH1 site sits at an elevation of 36.5 m below sea level, well below the Lake Cahuilla shoreline, but well above the 1907 highstand of the Salton Sea and the highest closed contour of Mesquite Basin. Indeed, detailed comparisons of U.S. Geological Survey (1908) with modern USGS topo maps reveal that, at its fullest and closest reach, Mesquite Lake was a number of meters lower than and at least two kilometers away from the BFZ paleoseismic sites. Given the historical constraints on lakes in the Salton Trough, it seems reasonable to assume that any lacustrine or deltaic deposits of substantial (a few cm or more) thickness are at least as old as the early 18th century.

In the trenches at Site BFH1 and in the boreholes at Site BFH2, the uppermost layers consisted of a sequence of anthropogenic fill. These units are numbered 210 and above on the trench logs (Figures 5–6) and are labeled “fill” on the borehole cross-section (Figure 7). The identification of these units as fill is based on several lines of evidence. Most commonly, these units are very to extremely poorly sorted, contain anthropogenic material such as Styrofoam, asphalt, or intact glass bottles, and/or contain granule-size lithic fragments with no apparent local source. (With the exception of clay pebbles found in certain sand units, grains the size of coarse sand and larger were generally not observed in the rest of the section.) In some cases, the material in these units is very loose, but in other places, these units are cemented and are harder than underlying layers. Units 210–228, which are present only on the downdropped side of F1w, have an intriguing downlapping geometry that is best explained as the result of bulldozing activity in which the uppermost layers of the upthrown side of the fault are incrementally scraped off and pushed westward toward and over the scarp, to build up the downthrown side in laterally successive wedges; most likely, such bulldozing activity would be done to grade the scarp, so that vehicles can easily traverse it. Units 210–228 presumably correlate with either the initial grading of Harris Road in the early part of the 20th century (prior to 1937) or the regrading of the road prior to its paving in 1970.

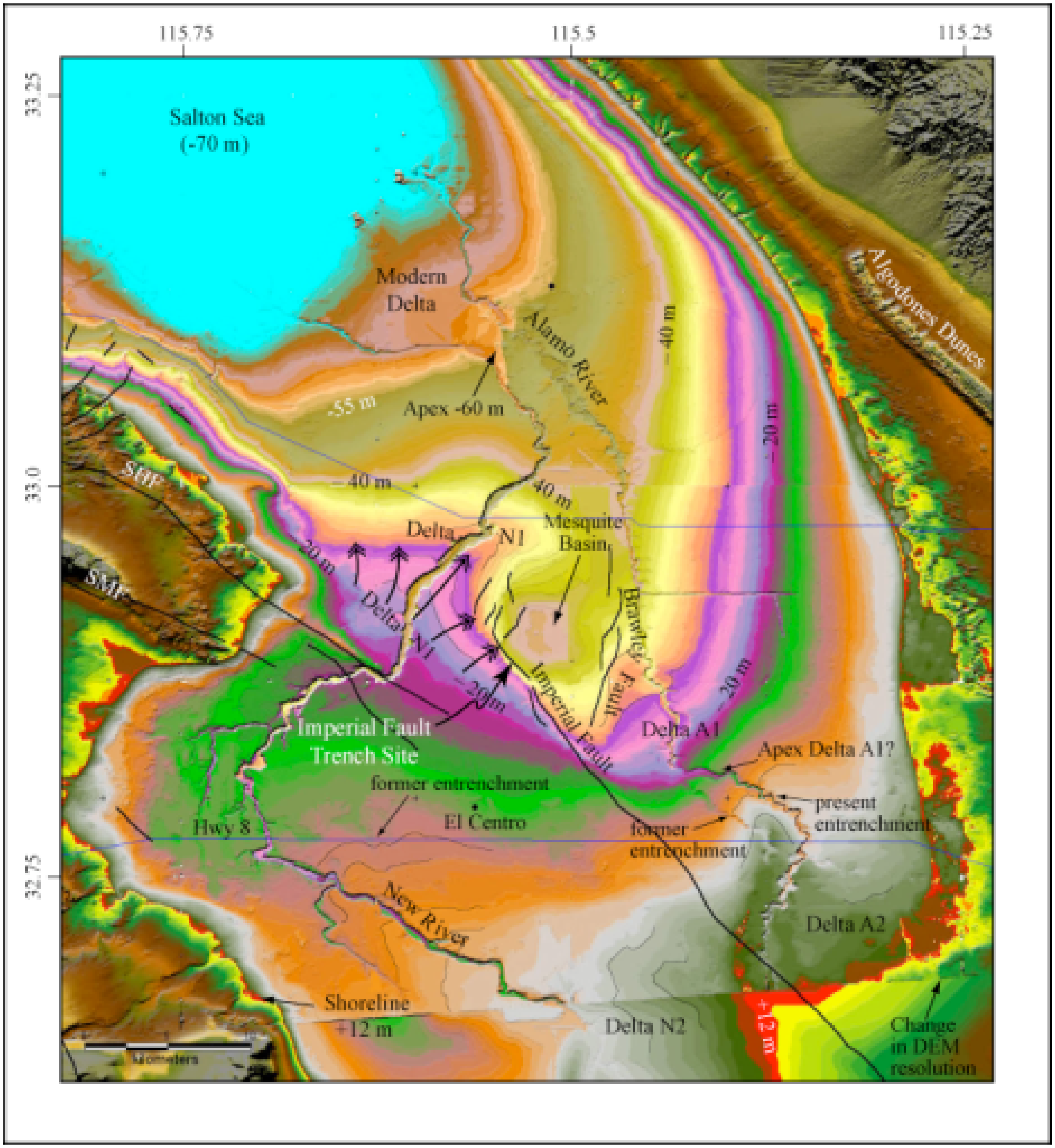

Figure 8. Southern Salton Trough deltaic system, based on DEM imagery. Color contours indicate elevation; each color band represents a 5–10 m change in elevation. Red contour line corresponds to the elevation of 12 m above mean sea level, which represents the highstand shoreline of Lake Cahuilla. Note the location of the modern delta, which is interpreted to have formed initially in response to the 1905–1907 filling of the Salton Sea; slow retreat of the lake combined with regular flow of the New and Alamo Rivers has built this modern delta that is prograding into the Salton Sea. In addition to the modern delta, four prehistoric delta lobes have been interpreted on this DEM: deltas N1 and N2 on the New River, and deltas A1 and A2 on the Alamo River. Main faults are mapped in black. SMF: Superstition Mountain fault; SHF: Superstition Hills fault. Modified from Ragona (2003).

Table 4: Radiocarbon Ages derived from Detrital Charcoal Samples

Sample (1)	Stratigraphic Unit (2)	$\delta^{13}C$ (3)	Uncalibrated ^{14}C Age, Years B.P. (4, 5)	Calibrated Calendric 2σ Max-Min Date Range (6)	Probability (7)
BFH-C-36	170	-25	37900 ± 400	too old for calibration curve	—
BFH-C-29	156	-25	105 ± 40	A.D. 1677-1762 A.D. 1803-1938 A.D. 1946-1955	0.328 0.645 0.026
BFH-C-33	154-156	-25	70 ± 40	A.D. 1683-1733 A.D. 1807-1929 A.D. 1947-1955	0.261 0.698 0.041
BFH-C-24	130	-25	80 ± 30	A.D. 1689-1729 A.D. 1810-1922 A.D. 1948-1955	0.249 0.712 0.039
BFH-C-25	130	-25	65 ± 40	A.D. 1684-1732 A.D. 1808-1927 A.D. 1947-1955	0.252 0.703 0.045
BFH-C-30	130	-25	70 ± 40	A.D. 1683-1733 A.D. 1807-1929 A.D. 1947-1955	0.261 0.698 0.041
BFH-C-35	128	-25	505 ± 40	A.D. 1325-1349 A.D. 1391-1455 A.D. 1456-1463 A.D. 1464-1467	0.099 0.888 0.010 0.003
BFH-C-46	110	-25	2335 ± 40	518-435 B.C. 435-356 B.C. 288-257 B.C. 247-233 B.C.	0.201 0.696 0.084 0.018
BFH-C-47	110	-25	4730 ± 140	3885-3885 B.C. 3795-3088 B.C. 3059-3039 B.C.	0.000 0.993 0.006
BFH-C-48	110	-25	4530 ± 200	3700-2855 B.C. 2855-2844 B.C. 2815-2675 B.C.	0.957 0.002 0.041
BFH-C-45	100	-25	2920 ± 35	1257-1236 B.C. 1214-1135 B.C. 1135-1003 B.C.	0.048 0.312 0.640
BFH-C-50	100	-25	2215 ± 45	385-175 B.C.	1.000
BFH-C-07 .11mgC	100	-25	2190 ± 50	384-145 B.C. 145-113 B.C.	0.952 0.048
BFH-C-90	75	-25	5775 ± 40	4766-4758 B.C. 4716-4524 B.C.	0.016 0.984
BFH-C-11	75	-25	5360 ± 100	4359-3973 B.C.	1.000
BFH-C-10	75	-25	2975 ± 30	1368-1361 B.C. 1315-1111 B.C. 1099-1078 B.C. 1060-1053 B.C.	0.008 0.960 0.023 0.009

Table 4 (continued)

1) All samples were single chunks of charcoal.
2) Stratigraphic units are numbered such that high numbered units are above (younger than) low numbered units. Unit numbering scheme is current as of 2 May 2004.
3) $\delta^{13}C$ values are the assumed values according to Stuiver and Polach (1977).
4) The quoted ^{14}C age is in radiocarbon years using the Libby half life of 5568 years and following the conventions of Stuiver and Polach (1977).
5) Sample preparation backgrounds have been subtracted, based on measurements of samples of ^{14}C-free coal. Backgrounds were scaled relative to sample size.
6) Uncorrected ^{14}C ages were dendrochronologically calibrated using Calib Rev 4.3 based on Stuiver and Reimer (1993) and Stuiver *et al.* (1998).
7) Relative area under 2σ probability distribution.

Below Units 210–250 in trench BFH1 West lie Units 170–176, whose nature is somewhat ambiguous. While units 172–176 appear to be weakly bedded and locally overlie Unit 170, the generally massive nature of Unit 170, the similarity of Unit 170 to overlying fill, and the lack of a sharp upper contact make Unit 170 in places difficult to distinguish from the fill; only by the geometrical relationships between the units do we infer that Unit 170 is a bona fide non-artificial unit. On the BFH1 West trench log (Figure 5), much of the upper contact of Unit 170 west of F1w is drawn as a dashed line; in these locations, the contact is mixed and irregular, and we could not locate the contact precisely.

Stratigraphically below Unit 170 lies a sequence of fine-grained channel-fill deposits. The scour-and-fill geometry of Units 140–160 and the small-scale cross-bedding in Units 142 and 160 imply a fluvial nature for these deposits. The age of these units is relatively well constrained by an *in situ* 1-m wide burn horizon near the top of underlying Unit 130 (see Figure 5). Unit 130, which will be discussed shortly, is inferred to be the uppermost portion of a sequence of deposits related to an infilling of Lake Cahuilla. Consequently, the upper contact of Unit 130 marks a transition from lacustrine to fluvial facies, and it represents local emergence of the former lake bottom to subaerial conditions. [At the time the burn horizon formed, the BFH1 site was probably near the shoreline of a gradually retreating Lake Cahuilla; it is conceivable that the burn horizon is the result of a campfire built by local Cahuilla Indians along or near the shore. It was not uncommon for fires from Cahuilla encampments to dot the shoreline of Lake Cahuilla at night (Modesto and Mount, 1980).] Calibrated two-sigma calendric ages from ^{14}C analyses of three charcoal samples from this burn horizon (see Table 4) constrain the age of all overlying units (units numbered 140 and higher) to be younger than A.D. 1689. Considering that the ground must have been subaerially exposed by the time of the burn, we further constrain Units 140 and higher to be younger than the desiccation at this site of the most recent Lake Cahuilla [dated by Sieh and Williams (1990) to have had its last highstand at ca. A.D. 1680]; using the average evaporation rate of Lake Cahuilla of 1.52 m determined by Sieh and Williams (1990), desiccation at this site would have occurred about 33 years (or more, if there was some Colorado River inflow into the lake) after the highstand.

Some or all of Units 140–160 may represent known historical occasions on which Colorado River water flowed into the Salton Trough. In the years 1840, 1849, 1852, 1859, 1862, 1867, 1891, and 1905–1907, large quantities of water passed into the Salton Sea through the New and/or Alamo Rivers (Barrows, 1900; Cory, 1913, pp. 1228, 1247). [Nothing is known about floods prior to 1840, although the period from ca. A.D. 1825 to 1840 apparently did not see any significant floods (Barrows, 1900). As mentioned previously, none of the 19th century infillings of the Salton Trough appear to have produced lakes that were larger than the 20th century Salton Sea.] Prior to 1905, the channels of the New and Alamo Rivers meandered and were comparatively shallow (Cory, 1913, p. 1410); the diversion of the Colorado River into the Salton Sea in 1905 caused the rivers to incise the deep, wide channels that characterize them today (Cory, 1913, pp. 1249, 1320; Sykes, 1937, pp. 117–119). Maps from 1905 (U.S. Geological Survey, 1907), 1908 (U.S. Geological Survey, 1908), and 1911 (Cory, 1913, Plate 46) show the Alamo and New Rivers in essentially the same courses they follow in the 1937 USDA aerial photos and today, at least near the latitude of Harris Road, from which we infer that the two rivers have not significantly altered their courses since they incised their channels (and since their flow was controlled) in 1905–1907. In contrast, a series of surveyor's maps from 1856 (Hays, 1856a–d) shows a "shallow arroyo" west of the present Alamo River but shows no channel at the present location of the Alamo River; unfortunately, the "shallow arroyo" is not drawn in the vicinity of Harris Road, so the arroyo's location relative to Sites BFH1 and BFH2 cannot be determined. In any case, while Units 140–160 in our trenches may represent deposition at any time between the desiccation of the A.D. 1680 lake and the beginning of incision in 1905, these units cannot plausibly be younger than A.D. 1905.

Units 120–130 are inferred to represent near-shore lacustrine and deltaic deposits. The nature of Unit 130 itself is ambiguous; it is silty and very fine to fine grained, and it is mostly massive, although faint irregular laminations can be observed in some locations, especially near its upper and lower contacts. The lower contact of Unit 130 is highly irregular, and there appear to be signs of soft-sediment deformation of this contact after deposition of some or all of Unit 130. Possible interpretations of this deformation are that it results from shaking-induced liquefaction or that it is a set of load structures that result from footsteps in the soft sediment near the shore, but the cause is not clear. Units 120–128 consist of a sequence of wavy, parallel-bedded 1–5-cm thick silty clays to silty fine sands. In that sequence a few beds stand out as being somewhat distinct: Unit 125 is siltier; Unit 123 is a silty clay; Unit 121 is a very fine to fine sand; and Unit 120w is a reduced silty sand.

The bulk of Units 100–116 is inferred to represent deeper-water lacustrine facies. Units 100 and 116 are both massive reddish clays that break apart in peds and which do not have prominent internal laminations. They are inferred to be the product of settling of suspended load in quiet lacustrine environments. Unit 110 is similar to Units 100 and 116, but it is siltier and laminated; the laminations cause this unit to appear "ledgy" in the trench wall when it dries. Unit 110 was probably formed under similar conditions as Units 100 and 116, but Unit 110 was probably formed closer to shore or closer to a sediment source such as a river delta. Under the classification of Van de Kamp (1973), Units 100, 110, and 116 would be considered lutite. Interbedded with Units 100, 110, and 116 are Units 112, 113, and 114, which are coarser-grained sandy deposits. Unit 112 is laminated. The exact nature of these deposits are ambiguous, but they might represent a period of subaerial exposure and deposition (possibly fluvial deposition) in between infillings of Lake Cahuilla.

Units 75–95 are interpreted to be fluvial and/or deltaic in origin. Starting at the base of this sequence and going up in section, Unit 75 is a small-scale cross-bedded silty very fine to fine sand. The upper and lower contacts of Unit 75 are roughly planar, except in the fault zones and in other isolated areas; the lower contact of Unit 75 is gradational over ~10 cm. East of fault F2, Unit 75 appears to have channeled locally into the underlying material; this channeling was evident a few meters east of F2 in the auger borehole profile (see Figure 7), and it is also apparent several meters farther south and east in the exposure in Mesquite Drain 2 (see Figure 4c). Whether these two exposures are of a single or distinct channels, the channeling presumably represents contemporaneous headward erosion into the upthrown block of fault F2. In the immediate vicinity of this channel, clay pebbles (which are inferred to be rip-up clasts from upstream) are present in the lower part of this unit; these clay pebbles were not observed elsewhere in the unit. Unit 80 is a pervasively planar-laminated fine sand with alternating light and dark laminations. Where original bedding is preserved, the upper and lower contacts of Unit 80 are typically planar. Units 91–93 are thin beds that appear to pinch out eastward toward fault F1e, possibly indicating that they were deposited over preexisting topography that was not present at the time of deposition of Unit 80. Unit 95 is a generally massive silty very fine sand, although faint internal bedding is detectable in places. West of fault F1w, in the uppermost ~20 cm of Unit 95, the very fine sand is interlayered with clay. In the vicinity of Site BFH1, the upper contact of Unit 95 is typically planar, and the lower contact is roughly planar; however Unit 95 pinches out eastward toward fault F2, which leads to the inference that Unit 95, like Units 91–93, was deposited over preexisting topography. We infer that Units 75–95 represent fluvial or deltaic facies; the channelized base of Unit 75 just east of F2 is inferred to be either a channel within the delta or a small channel within the broader river channel.

Units 75–95 are also consistent with Van de Kamp's (1973) description of meandering channel facies. From bottom to top, a complete fining upward sequence consists of active channel fill, partial abandonment fill, and abandoned channel fill (Meckel, 1972). According to Van de Kamp's (1973) observations, active channel fill deposits of the Alamo River are typically fine to very fine grained, well to very well sorted, horizontally laminated or medium-scale cross-bedded sands, commonly with a basal lag of clay pebble clasts; partial abandonment channel fill is characterized by well sorted, very fine sands that are laminated or locally small-scale cross-bedded, and by laminated and ripple-bedded silts with interlayered clays; abandoned channel fill is composed of laminated clay and silt. In this sequence, the abandoned channel fill is commonly indistinguishable from lacustrine silt and clay due to its similar character and the intimate association of the two (Van de Kamp, 1973). In the Harris Road section, Units 75–80 are consistent with active channel fill, Unit 95 is consistent with partial abandonment channel fill, and part of Unit 100 may represent abandoned channel fill, which in this case would be indistinguishable from the overlying lacustrine deposits.

The ages of Units 75–130 are constrained by radiocarbon analysis of a number of detrital charcoal samples and by OSL dating of two sediment samples (see Tables 4–5 and Figures 5–6). Unfortunately, many of the samples used for ^{14}C dating give ages that are out of sequence; the most plausible explanation for this is that the samples have a variable and sometimes significant inherited age prior to deposition. Consequently, the maximum age of any unit is best constrained by the youngest sample in any underlying units. As such, the calibrated two-sigma calendric age of sample C-35 in Unit 128 constrains Unit 130 and the upper part of Unit 128 to be younger than A.D. 1325; to the extent that Units 120–128 were deposits in rapid succession, these units cannot be much older than the uppermost part of Unit 128. Similarly, samples C-07 and C-50 in Unit 100 constrain the upper part of Unit 100 and all stratigraphically higher units to be younger than 384 B.C., and sample C-10 in Unit 75 constrains the uppermost part of Unit 75 and higher units to be younger than 1368 B.C.

Table 5: Ages derived from OSL Samples

Sample #	[U] (ppm)	[Th] (ppm)	[K] (%)	[Rb] (ppm)	Dose Rate (Gy/ka)	Age using original dose (ka)	Mean of 3 doses (Gy/ka)	Age based of 3 doses (ka)	Mean of two 2 doses (Gy/ka)	Age based on 2 new doses (ka)
OSL-75	1.68	7.64	2.0	81.6	2.82±0.18	**3.3±0.4**				
OSL-75b	2.19	7.6	2.1	76.2	3.04±0.20					
OSL-75c	2.26	7.77	2.1	80.2	3.05±0.20		2.97±0.33	**3.2±0.5**	3.04±0.28	**3.1±0.4**
OSL-80	0.95	4.48	1.5	60.8	2.07±0.14	**4.9±0.5**				
OSL-80b	1.28	5.14	1.8	60.9	2.38±0.16					
OSL-80c	1.69	5.34	1.8	62.9	2.53±0.17		2.33±0.27	**4.4±0.6**	2.46±0.23	**4.1±0.5**

Although the charcoal samples provide a maximum age for all overlying units, it is not clear from the radiocarbon analysis alone how tight the maximum-age constraints are, as it is possible that *all* of the charcoal samples in Units 75–128 have an inherited age of several hundred to several thousand years. Samples from Units 75 and 80 were independently dated using OSL techniques (see Table 5). Assuming our interpretation that these deposits are fluvial or deltaic in origin is correct, these deposits should be good candidates for OSL dating, as individual sand grains should have been exposed to light and "reset" at the time of or in the hours before their deposition.

Unfortunately, although the OSL age of Unit 75 appears to be reasonable (3.2 ± 0.5 ka), the two ages are reversed, and the OSL age of Unit 80 is about 1000 years too old: Unit 80, which is stratigraphically younger than Unit 75, has an OSL age which is about 1000 years older than that of Unit 75 and likewise about 1000 years older than permitted by the radiocarbon analysis discussed previously. If we ignore the OSL result from Unit 80 but assume that the result from Unit 75 is correct within its stated uncertainty, then it appears that radiocarbon sample C-10 in Unit 75 did not have a significant inherited age, and that the maximum age inferred from the radiocarbon analysis for the uppermost part of Unit 75 and higher is robust.

Given the apparent age of Units 75 and above, and given the observation that the only lacustrine facies within Units 75 and above occurred exclusively in Units 100–130 (and in the uppermost part of Unit 95), we infer that Units 100–130 represent *all* of the lakes within the last few thousand years that filled the Salton Trough to an elevation of –36 m or higher, although the infilling of the earliest of those lakes may be partly represented by Units 75–95. Although there is evidence for minor scouring and local erosion of some of the lake deposits of the last few thousand years, there is no evidence for widespread erosion (*i.e.*, scouring that is wider than the length of the trench) of significant portions of the lake deposits. Furthermore, we consider it unlikely for there to be significant erosion on the downdropped side of the BFZ.

We know from trenches at the Lake Cahuilla shoreline (13 m above sea level) that there were four Lake Cahuilla highstands in fairly rapid succession between A.D. 1440 and ca. A.D. 1680 (Gurrola and Rockwell, 1996). Nearby, at sea level, there is evidence for four distinct lakes between A.D. 1630 and ca. A.D. 1680 (Orgil, 2001). Orgil (2001) argued that the three most recent lakes at the sea level site correspond one-for-one with the three most recent highstands at the shoreline site of Gurrola and Rockwell (1996), whereas the fourth lake back at the sea level site represents a partial filling (the lake appears to have peaked at an elevation slightly above sea level but below +13 m, and therefore this partial filling would not be seen in the record at the shoreline site) that was followed by brief desiccation (to below sea level) and eventual re-filling to the +13 m shoreline. The fourth lake back at the shoreline site of Gurrola and Rockwell (1996), which is dated at A.D. 1440–1640, does not appear to be present at the sea level site, because it is older than a major erosional event that removed part of the sedimentary record there (Orgil, 2001). In the time between the most recent series of lakes, the lake would not have had sufficient time to desiccate completely; if in this time period, however, the lake level fluctuated on a scale of several decades between 13 m above sea level and ~30 m below sea level [which is possible assuming the vertical evaporation rate of 1.52 m/yr determined by Sieh and Williams (1990)], one might expect a depositional sequence similar to that observed in Units 120–128. In light of this information, and given the observation that there are no younger lacustrine deposits in the trench, we propose that Units 120–130 represent, at least in part, the lakes between A.D. 1440 and ca. 1680.

An inspection of a DEM-based topographic map (Figure 8) reveals that the BFH1 site sits on the margin of a prehistoric Alamo River delta (delta A1). Delta A1, and its presumably contemporaneous counterpart on the New River (delta N1), extend northward and downward from an elevation of ~19 m below sea level; Ragona (2003) interpreted that these bodies prograded northward from a temporally stable –19 m Lake Cahuilla paleoshoreline. The timing of these deltas are not well constrained, although they must predate the A.D. 1680 highstand: oral traditions by the native Cahuilla (Modesto and Mount, 1980) and historical accounts (Emory, 1848; Blake, 1854, 1915; Barrows, 1900; Cory, 1913, p. 1228; Sieh and Williams, 1990) collectively preclude a significant still-stand at this level at any time since the A.D. 1680 lake. The delta must also be young enough to still be recognizable in the present topography. Any or all of Units 120–130 may be associated with this delta; alternatively, to the extent that Units 75–95 are deltaic in origin, they may be associated with the delta instead.

If Units 100–116 represent multiple lake highstands, it is not well understood why little non-lacustrine deposition is preserved between Units 100 and 116. Possible explanations include: (*a*) that in that time, Lake Cahuilla rarely or never desiccated fully, leaving the BFH1 site submerged for most of the last few thousand years; (*b*) that the site was subaerially exposed for extensive periods of time, but little subaerial deposition occurred in that time; or (*c*) that significant subaerial deposition occurred between late Holocene highstands of Lake Cahuilla, but significant unrecognized erosion erased almost all of this record. Native Cahuilla legends tend to preclude possibility (*a*) (Barrows, 1900; Modesto and Mount, 1980).

Below Unit 75 lies Unit 70, which is a clayey silt that grades reversely down to a silty clay. Unit 62 is a massive true sticky clay, similar to Unit 100; although this unit was observed only well below the water table, the minimal porosity of this unit caused it to have a relatively low water content. Unit 60 is similar to Unit 62, but Unit 60 is finely and pervasively laminated and appears to have an even lower water content. Because only the upper part of Unit 70 was exposed in the trenches, and because the lower part of Unit 70 and all lower units were revealed only in the auger boreholes, little is known about the stratification of these units. Furthermore, no samples (with which to date the lower units) were collected from below Unit 75, so there we have no maximum age for these units.

Although there is no evidence of missing section on the downthrown (west) side or immediately east of fault F1w, it is clear that some layers or portions thereof have been removed (both by natural channelization and by anthropogenic means) between F1w and F1e, and a significant part of the section is missing east of F1e. At site BFH2, a significant part of the section is missing east of F2, although most if not all of the section appears to be intact immediately west of F2. Of particular concern are the observations that Units 95 and above and the uppermost part of Unit 80 were removed from the upthrown side of fault F1e, and that Units 100 and above and the uppermost part of Unit 80 were removed from the upthrown side of fault F2, apparently when the respective scarps were planed off at some point in the historical period.

We will attempt to estimate the thickness of the missing section east of F1e, but we do not have sufficient information to reasonably estimate how much is missing east of F2. Based on measurements of the thickness of Unit 100 where it appears to be entirely preserved—in the lower bench of trench BFH1 West, in trench BFH1 East, and in the two westernmost boreholes (those at meter-marks 20 and 23) at Site BFH2—Unit 100 appears to have a uniform original thickness of ~80 cm. Indeed, we should expect a fairly uniform thickness for Unit 100: considering that Unit 100 predominantly represents settling of suspended load under a deep water column, and that Unit 100 would be draped over any preexisting topography, there should not be a significant difference in the thickness of Unit 100 over several hundred meters laterally, or over a difference in elevation of at most a few meters (a small fraction of the total height of the water column). For Unit 95, we cannot automatically assume a uniform thickness; however, in an exposure on the wall of Mesquite Drain 2 located 145 m east of F1e or 17 m west of F3 (see Figure 3), Unit 95 is 91 cm thick, which implies that Unit 95 is as thick or slightly thicker immediately east of F1e than it is to the west; for our best estimate of its thickness, we will assume Unit 95 maintains its 75-cm thickness over the 4-m-wide fault zone at F1e.

The irregular contact between Unit 80 and the overlying artificial fill east of F1e suggests that an unknown amount of Unit 80 was removed from the upthrown side of F1e. Immediately west of F1e, Unit 80 has a fairly uniform thickness of ~70 cm; immediately east of F1e, Unit 80 appears to have been at least 90 cm thick, based on the maximum observed preserved thickness. The greater thickness of Unit 80 on the upthrown side of F1e in trench BFH1 East suggests (a) that there was probably little (if any) topographic relief across F1e at the time of deposition of Unit 80; (b) that there has probably been significant strike-slip displacement across F1e since deposition of Unit 80; and (c) that there is probably not much of Unit 80 missing from the east side of F1e. Hence, our best estimate of the original thickness of Unit 80 east of F1e will be our minimum estimate, 90 cm.

A LOWER SEDIMENTATION RATE?

In the course of our work, we recognized one possible inconsistency between our findings and a commonly held belief about the Holocene sedimentation rate for the Imperial Valley. In his 1973 paper, Van de Kamp asserts that Holocene deposits in the Imperial Valley are roughly 60 to 100 m thick, although the limited data in his paper do not appear to support such an estimate. A thorough search of published literature has not revealed a revised estimate of that thickness. However, our findings indicate either that the rate of sedimentation varied considerably with time or that Van de Kamp's estimate is too high.

We will first focus on the downdropped (west) side of fault F1w, where the sedimentation rate has necessarily been higher than elsewhere in our trenches across the BFZ. Here, the base of Unit 100 is ~3.5 m below the base of the historical fill. If Units 100–130 represent all of the lakes within the last few thousand years that filled the Salton Trough to an elevation of –36 m or higher, then the lake that Gurrola and Rockwell (1996) determined to have had its highstand at A.D. 887 +77/–70 must be included in those units. Consequently, the A.D. 817–964 date range represents the minimum age of the base of Unit 100, and the 3.5-m thickness of Units 100–170 provides a maximum constraint on the amount of deposition at this site between ca. A.D. 887 and the beginning of agriculture in the Imperial Valley in the early 20th century. Of course, it is possible that there were other lakes prior to the A.D. 887 lake but younger than Units 75–80; Gurrola and Rockwell (1996) identified one other Lake Cahuilla highstand at the shoreline, some time between the A.D. 887 lake and 4674 B.C. If that is the case, then the 3.5 m of section in consideration represents a longer time span of deposition than ~1000 years, and it suggests a corresponding slower sedimentation rate. Nonetheless, using our conservative estimate for the last 1000 years, if the rate of 3.5 m of sedimentation per thousand years is appropriate for the entire Holocene, then the total thickness of Holocene deposits at this site is at most 35 m; this is much lower than Van de Kamp's (1973) range of 60–100 m for the entire Imperial Valley. Two possible explanations for this inconsistency are that the sedimentation rate was much higher in the early- to mid- Holocene than during the last 1000 years, or that Van de Kamp's (1973) estimate is too high.

Different authors have assigned a purely tectonic origin to Mesquite Basin (*e.g.,* Keller, 1979) based on the dip components of slip along the Brawley and northern Imperial faults, and on the thickness of the sedimentary sequence in the vicinity of the basin. In light of this commonly held belief, one might expect that the rate of sedimentation observed on the downthrown side of fault F1w in the Mesquite Basin would be among the highest rates anywhere in the Imperial Valley. As Ragona (2003) points out, however, tectonic subsidence between the Brawley and Imperial faults may not be as important as previously considered. The sedimentary thickness reaches a maximum of 7 ± 1 km at Mesquite Basin, but the sedimentary package also has roughly the same thickness to the east of the BFZ (Keller, 1979; Fuis *et al*. 1982), which implies that this fault does not control the formation of the depression as much as was once thought. In addition, analysis of a DEM of the Imperial Valley reveals that presumably contemporaneous deltas of the New and Alamo Rivers (deltas N1 and A1, respectively) surround Mesquite Basin, leaving the basin as a topographic low between the surrounding delta lobes (Ragona, 2003; Figure 8). Ragona (2003) suggested that *both* the relatively low sedimentation in Mesquite Basin and tectonic subsidence of the basin have contributed significantly to its formation. This argument is consistent with our observation of a low sedimentation rate west of the BFZ in Mesquite Basin.

A similar exercise immediately east of F1w, where little, if any, section was lost due to grading, reveals that only ~2.5 m of sediments have been deposited in the 1000-year (or longer) period between the deposition of the base of Unit 100 and the beginning of agricultural influence in sedimentation patterns.

SLIP HISTORY, BASED ON PALEOSEISMIC EVIDENCE

One of the common goals of paleoseismology is to ascertain details (such as the size and timing) of individual past events on a fault. Unfortunately, this is not possible at the BFZ site. The main reasons for this limitation are geological. First, because an apparently significant amount of slip along the BFZ is accommodated by creep or in small-slip events (such as 1975 or 1979), individual faulting events do not always produce fissures, colluvial wedges, or other common signatures of event horizons, and fault strands do not always have abrupt upward terminations, even at known event horizons; these issues make it potentially difficult to recognize all event horizons. Second, because the event recurrence time might be short relative to the average periodicity of sedimentation (especially in light of the modern event recurrence intervals), it is highly probable that multiple events are recorded at some event horizons. Third, in lacustrine environments in which deposition is achieved solely by settling of suspended load, any scarps that form are typically preserved, and growth strata are typically not deposited unless deposition becomes dominated by fluvial, deltaic, or other processes; this leads to the possibility that event horizons within clay units might not be recognizable, and that it might not be possible to distinguish between a single (comparatively large) event at the end of a lake highstand and a single event or multiple smaller events at different times within the lake's history. And fourth, because the BFZ is complex and we cannot guarantee that we have identified every strand, it is possible that some events did not break the strands we have examined. In addition to these geological limitations, anthropogenic modification of the ground surface (and in particular, removal of portions of the stratigraphic section at certain faults) has entirely removed some information from the geological record.

Instead of attempting to recognize individual events, we will attempt to determine the amount of vertical displacement that occurred on the faults during key stratigraphic intervals. Considering that slip at this site in the historical period was predominantly vertical, we will compare the vertical displacement seen in the paleoseismic record with vertical slip documented in the historical period. To the extent that vertical displacement is representative of total slip at both time scales, this can be a useful comparison.

SLIP ACROSS FAULT F1W

As mentioned previously, we constrain Units 140–160 to predate the historical incision of the modern channel of the Alamo River in A.D. 1905–1907. Thus, the extent to which Units 140–160 are displaced across fault strand F1w represents the maximum amount of displacement that could have occurred as discrete surface slip across F1w since 1905. (This value provides a maximum constraint because some of the measured displacement could have occurred prior to 1905.) Unfortunately, a large burrow in the fault zone in the main exposure of trench BFH1 West destroyed the faulting relationships and displacements recorded in Units 140–160 in that exposure (see Figure 5), but the wall was cut back and re-logged in the vicinity of the fault zone; the log of the new cut, which was ~40 cm south of the original cut, is also shown in Figure 5. Using the log of the new cut, we "unslipped" the two sides of the fault to construct a restored section in which Units 140–160 project across the fault with minimal displacements (see Figure 9). We find that "undoing" 8.7 ± 0.8 cm of vertical displacement provides the most reasonable restoration of Units 140–160 across fault F1w, although changes in the thickness of certain units across the fault suggest that there was also a significant amount of strike slip. Surprisingly, the apparent vertical displacement in the trench wall since 1905 is less than the amount of dip slip across F1w (~14 cm) measured at Harris Road between 1970 and 1979. One possible explanation for this apparent paradox is that some of the offset measured in the leveling profiles 30 cm north of the southern edge of Harris Road (Sharp and Lienkaemper, 1982) could be taken up as tilting or warping ~7 m farther south in the trench wall; this would be permitted by the stratigraphy in the trench, which dips westward in the fault zone, although some of the dip almost certainly is primary (*i.e.*, bedding draped over a scarp). Nonetheless, if the entirety of the vertical relief of Units 158 and 160 over a 5-meter aperture centered on fault F1w is assumed to be a product of post-depositional tilting (*i.e.*, if Units 158 and 160 were horizontal when originally deposited across F1w), then the amount of vertical separation across the F1w fault zone since 1905 could not exceed ~30 cm. It is apparent, then, that at least half of the motion along F1w since 1905 occurred within a relatively narrow 9-year window between 1970 and 1979. Between 1905 and 1970, the average rate of slip across F1w could not have exceeded 2.5 mm/yr, which is much lower than the average rate of at least 4.3 mm/yr observed between 1970 and 2004.

By a similar reconstruction, one can constrain the amount of vertical displacement across F1w since ca. A.D. 1710. If Unit 128 was deposited flat across F1w, then its upper contact has been displaced ~60 cm across the fault, including any tilting within several meters of the fault. Because Unit 128 could not have been deposited after the level of Lake Cahuilla dropped below the elevation of the trench site in ca. A.D. 1710, 60 cm is the maximum amount of vertical displacement that could have occurred across F1w since A.D. 1710. If, however, Unit 128 is older than A.D.

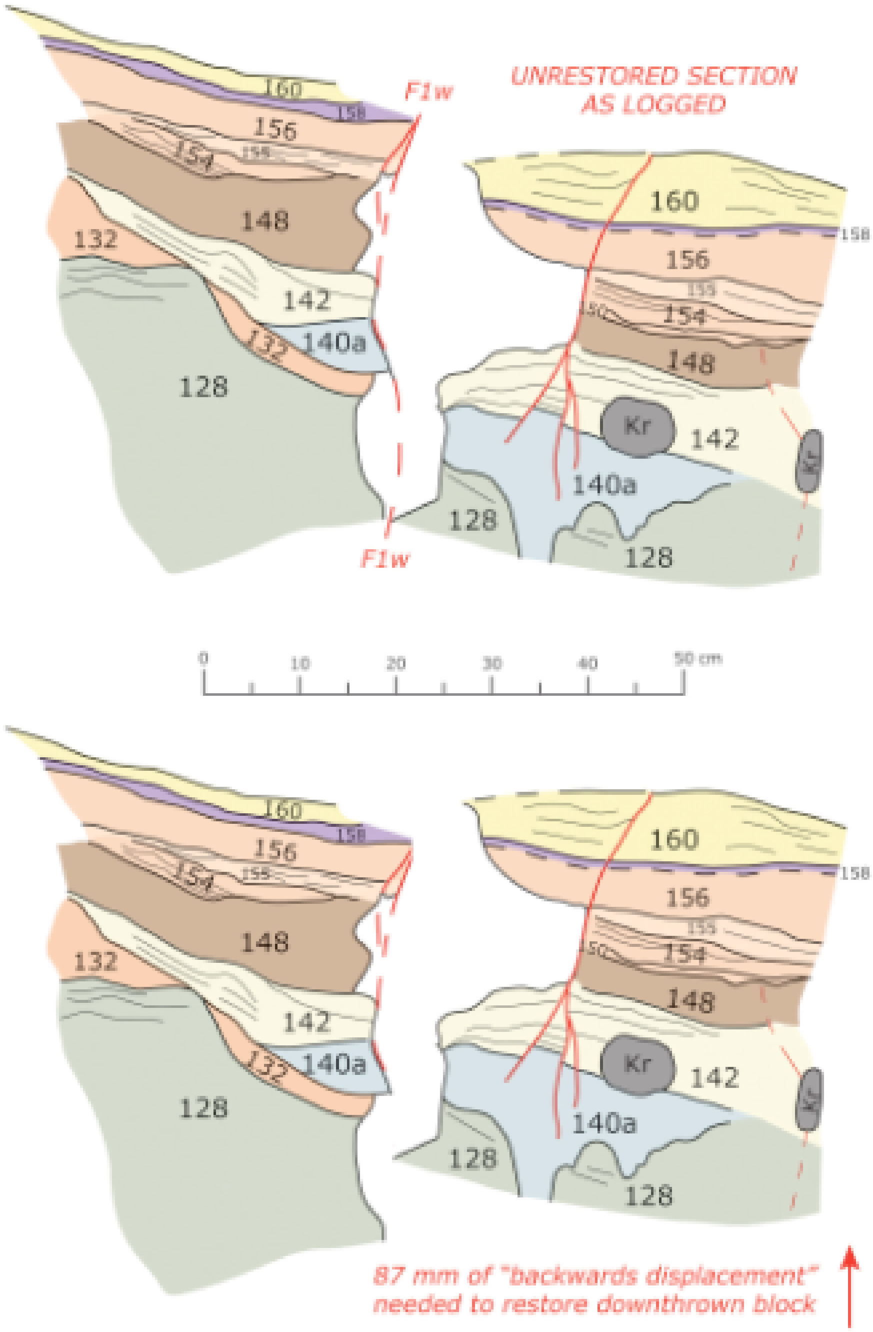

Figure 9. Restoration of uppermost stratigraphy across fault F1w. Top: the present situation. Bottom: most likely restoration of the section to its position immediately after deposition of Unit 160. In the bottom figure, 87 mm of vertical displacement has been “undone”; we find that “undoing” a vertical displacement of anywhere in the range 87 ± 8 mm provides a reasonable restoration, but discrete vertical displacements that are larger or smaller than that range yield less plausible restorations.

1710, and/or if the upper contact of Unit 128 was originally higher immediately east of F1w, then the amount of displacement since 1710 could be less than 60 cm. Using the cumulative slip value of 60 cm, the highest possible average rate of slip between A.D. 1710 and A.D. 1970 is 46 cm in 260 years, or 1.8 mm/yr; the highest possible average slip rate between A.D. 1710 and A.D. 2000 is 60 cm in 290 years, or 2.1 mm/yr.

Finally, we can constrain the vertical slip rate across F1w since the deposition of Unit 95. On the downthrown side of F1w, the top of Unit 95 was observed only within a meter of the fault, so we cannot be sure that we have captured in our aperture of observation all of the tilting; nonetheless, by following the deformation of overlying units, we can conservatively estimate the total vertical displacement, including tilting, of the upper contact of Unit 95 to be 2.5–2.8 m. The age of Unit 95 is loosely constrained to be older than A.D. 964 [based on the A.D. 887 +77/–70 age of the lake identified at the shoreline by Gurrola and Rockwell (1996); see earlier discussion] but to be younger than 1368 B.C. [based on the maximum age of charcoal sample C-10 in Unit 75]. The maximum, minimum, and "median" long-term vertical slip rates across F1w, computed using displacements of 2.8, 2.5, and 2.65 m, and time periods of 1040, 3372, and 2206 years, respectively, are 2.7, 0.74, and 1.2 mm/yr. Note that the minimum slip rate accounts for the possibility that Unit 95 was not originally deposited horizontally across the fault: the uniform thickness across F1w of Unit 80 (which is a laminated sand interpreted to have been deposited in a deltaic or meandering channel environment) implies that there was no topographic relief across F1w during or immediately after deposition of Unit 80. All apparent vertical displacement of the top of Unit 95 was necessarily produced after deposition of Unit 80. As the age of Unit 80 is constrained by the same charcoal sample to be younger than 1368 B.C., the possibility that Unit 95 was not originally deposited horizontally does not lower the minimum vertical slip rate of 0.74 mm/yr.

SLIP ACROSS FAULT F1E

Because of the section that has been removed in the vicinity of fault F1e, we have no constraints on the offsets across F1e of the youngest units. Nonetheless, we can constrain the offset of the top of Unit 95 across F1e. Based on the section that remains intact, the vertical offset of that contact is at least 0.5 m, but this value is a minimum because the top of Unit 95 may have been significantly higher than the base of the fill on the upthrown side of the fault. If (as we inferred earlier) Unit 95 maintained its 75-cm thickness across F1e, and if (as we also inferred) Unit 80 was 90 cm thick immediately east of F1e, then the amount of vertical offset on the top of Unit 95 across F1e would total 1.35 m. Warping and secondary faulting in trench BFH1 East could roughly accommodate an additional 0.5 m of vertical separation of that contact, including 0.15 m on a single secondary strand 6 m west of F1e. For our maximum constraint on the amount of offset of the top of Unit 95, we will use 1.85 m; for our minimum constraint, we will use 0.65 (the 0.5 m minimum across F1e plus the 0.15 m observed across the secondary fault); and for our best estimate, we will use 1.50 m (the inferred 1.35 m across F1e and the additional 0.15 m across the secondary fault). We will use the same time constraints as in the previous paragraph for this contact. Hence, the maximum, minimum, and "median" vertical slip rates across F1w since deposition of Unit 95 are 1.8, 0.19, and 0.68 mm/yr.

SLIP ACROSS FAULTS F3 and F4

Our ability to make quantitative observations at faults F3 and F4 is severely limited, partly because of the superficial nature of the work we did at those sites, but mostly because of the removal of a significant portion of the section there. Continuing west to east, there appears to be a slight west-side-up component to the slip at fault F3, as the base of Unit 100 is roughly 10–20 cm higher to the west (see Figures 4 e–f), but this apparent dip component of slip may be entirely the result of juxtaposition by strike slip motion of higher topography to the west of the fault against lower topography to the east.

Farther east, we identified another possible fault (F4) based partly on an apparent east-side-up step of ~10 cm in the base of Unit 100 in the wall of Mesquite Drain 2 and based additionally on a coincident vegetation boundary (hereinafter referred to as the "F4 vegetation boundary") in the agricultural field due south of this inferred offset in the canal wall (see Figures 4 g–h); due to difficult accessibility, however, we were unable to clean off the exposure in the drain wall. At this point, we should comment on the potential significance of the F4 vegetation boundary. West of the boundary, alfalfa has been planted, but east of the boundary within the same field, Bermuda grass is growing. It is not common in the Imperial Valley to find different crops growing together in the same field as they do here, but this uncommon relationship also exists in the field immediately to the west; in the field to the west, the vegetation boundary is roughly coincident with fault F1w, with alfalfa to the west and Bermuda grass to the east. (We will hereinafter refer to this as the "F1w vegetation boundary.") According to Mr. Mark Osterkamp, a land owner and farmer in the Imperial Valley, Bermuda grass will grow in highly saline soil, whereas alfalfa will not. Mr. Osterkamp owns the field immediately north of Harris Road that straddles fault F1w and is familiar with the F1w vegetation boundary: when the original farmers graded their fields across F1w and removed the excess material from the upthrown side of F1w, they discovered that the soil that remained east of the fault was too saline to grow alfalfa; even today, only Bermuda grass will grow there. Although Mr. Osterkamp is not familiar with the F4 vegetation boundary, we can speculate from the presence of the Bermuda grass that the soil east of the F4 vegetation boundary is more saline than the soil immediately to the west. However, it remains inconclusive whether the F4 vegetation boundary is controlled by a fault. The field containing the F4 vegetation boundary is topographically lower than the adjacent field to the east. (Fault F2 lies near the boundary of the two fields.) From Mr. Osterkamp's experience, where there is an elevation difference between two adjacent fields, some salt can leach down from the higher field into the lower field simply from the gravity-driven downward flow of water; to his knowledge, this leaching occurs independently of the location of faults. Hence, although we may reasonably assume that the soil immediately east of the F4 vegetation boundary is saltier than the soil immediately to the west, the higher salinity to the east does not necessarily imply the existence of a fault at the F4 vegetation boundary, nor does it imply that any material has been removed from the area immediately to the east of that boundary. The existence of fault F4, therefore, remains questionable.

SLIP ACROSS FAULT F2

The series of auger boreholes dug across fault F2 allows us to place crude constraints on the amount of displacement and the rate of slip across F2. As a conservative estimate, the base of Unit 100 is offset vertically a minimum of 1.5 m, based on the difference in depths to the base of Unit 100 in the auger hole at the 18-m mark, and to the base of the fill in the hole at 12 m (see Figure 7). As in trench BFH1 East, though, the base of Unit 100 was probably higher than the present base of the fill in the hole at 12 m. A maximum constraint on the displacement of the base of Unit 100 can be found by following the base of Units 75–80: as long as the base of Units 75–80 is examined outside of any local channels, the amount of separation on the base of Units 75–80 across F2 should be equal to or larger than the displacement of the base of Unit 100. The base of Units 75–80 is 2.0 m lower in the hole at 18 m than at 12 m; hence, the amount of discrete offset of the base of Unit 100 across F2 should not exceed 2.0 m. (Note that the hole at 12 m appears to be beyond the channel with its thalweg at the 4-m mark, although the 3-dimensional geometry may be more complicated than is apparent in this 2-dimensional punctuated snapshot.) Additional off-fault tilting is possible, however, as the bedding within the fault zone appears to dip slightly westward, as observed in the exposure in Mesquite Drain 2 (see Figure 4c). By analogy to observations at faults F1w and F1e, we estimate that tilting could accommodate up to 50 cm of additional slip. For our maximum, minimum, and "median" constraints on the amount of offset of the base of Unit 100 across F2, we will use 2.5, 1.5, and 2.0 m, respectively; we will use the same time constraints as for fault F1w and F1e. Hence, the respective maximum, minimum, and "median" vertical slip rates across F2 are 2.4, 0.44, and 0.91 mm/yr.

SLIP RATE ACROSS THE ENTIRE BFZ

To summarize, we can compute the maximum, minimum, and best estimates of the long-term slip rate based on the Unit 95 / 100 contact. Adding the amounts of slip constrained on F1w, F1e, and F2, and ignoring the presumably small contributions from F3, F4, and any unrecognized faults, we have a total offset of that contact of between 4.65 m and 7.15 m, with a best estimate of

6.15 m. Using the age constraints discussed earlier, we get a preferred vertical slip rate of 2.8 mm/yr, with possible values in the range 1.4–6.9 mm/yr. Between 1970 and 1979, 20.9 cm of vertical slip was documented, for a short-term vertical slip rate of 23 mm/yr. The vertical slip rate between 1970 and 1979 was clearly and significantly higher than the long-term rate, both across F1w and across the entire BFZ at Harris Road. Between 1970 and 2004, a minimum of 21.5 cm of vertical slip occurred across the entire BFZ at Harris Road, but this value may underestimate the actual value by a significant factor. Using the value, the average vertical slip rate between 1970 and 2004 must be at least 6.3 mm/yr.

EVIDENCE FOR EVENTS

As mentioned earlier, we will not attempt to determine the number of events recorded in our trenches on the BFZ, as it would be a fruitless and pointless exercise. Nonetheless, we will now briefly list the evidence we were able to document for events at various horizons. At the top of Unit 128 (base of Unit 140) in trench BFH1 West, multiple abrupt fault terminations and filled-in fissures suggest that an event or series of events occurred after deposition of Unit 128 but prior to deposition of Unit 140 (the most prominent fissure is filled in by Unit 140a; additional evidence comes from the observation that the vertical separation across the fault of the top of Unit 128 is greater than the separation of any overlying unit (note that Units 140-156 comprise a thin growth section). As an aside, the Unit 128 sand appears to be deformed in a brittle manner, suggesting that these (and all subsequent events) occurred under subaerial conditions, when the ground was not saturated; in other words, Lake Cahuilla had already desiccated to below this elevation by the time these earthquakes occurred. This observation is consistent with the inferred depositional environments of all stratigraphy above Unit 130.

In addition to the events at the top of Unit 128, significant offset of Units 116 and below, coupled with a thick growth section (Units 120–128) on the downdropped side of fault F1w, suggests that an event or series of events occurred during the course of the deposition of Units 100-116 and/or soon thereafter. At the top of Unit 95 (base of Unit 100) in trench BFH1 East, multiple abrupt fault terminations and filled-in fissures (especially the fissure in the secondary fault strand 6 m west of F1e; see Figure 6) suggest that a moderate event, perhaps as large as 1979 or larger, occurred after deposition of Unit 95 but prior to deposition of Unit 100. Finally, note that there appear to be at least two generations of fault strands within the main F1e fault zone (see Figure 6): the faults in blue (which are inferred to be the older generation) appear to have been tilted (along with the stratigraphy, to which the blue faults are still roughly perpendicular) by a younger generation of faults, namely those faults in red.

DISCUSSION

This study documents evidence for a long-term vertical slip rate of 2.8 (+4.1/–1.4) mm/yr across the oblique-slip BFZ at Harris Road. Despite the considerable uncertainty in this rate, it is lower than the modern rate (since 1970), and it is considerably lower than estimates of the strike slip rate on the SAF, which feeds into the BFZ. It is possible that we have missed some minor strands of the BFZ in our investigation of prehistoric slip, but, given our ability to follow the stratigraphy along most of the agricultural drain that crosses the BFZ just south of Harris Road, it is unlikely that we are missing a substantial amount of prehistoric vertical slip. If modern behavior is any indicator (in terms of the ratio of horizontal to vertical components of slip), then the long-term rate of strike slip across the BFZ should be lower than the long-term rate of vertical slip, at least in the vicinity of Harris Road. However, evidence suggests that this ratio may vary considerably over time: as Sharp (1982b) observed, in some localities on the Imperial fault and in the BFZ, the ratio of vertical to horizontal components of slip for the 1979 displacement differed substantially from those for other displacements from 1940 to present. Nonetheless, the rate of vertical slip observed historically is not representative of the average vertical rate over the past century and longer, and to the extent which the vertical slip rate is representative of the net rate of slip, the same contrast can be made for overall slip.

Variability in slip rate has also been documented along the southern SAF at Indio, although the recent and modern rates there have been lower than the apparent long-term average. Along the

SAF at Indio, Sieh (1986) and Sieh and Williams (1990) suggest a slip rate of 30 mm/yr for the period from A.D. 1000 to A.D. 1700 but only 3.4 mm/yr from A.D. 1700 to the present and 2 mm/yr since 1949. This is in contrast to the rate of 18–22 mm/yr for the southern SAF determined over a broader aperture by geodetic methods (Sauber, 1989; Lisowski *et al.*, 1991). The variability in slip rate over a matter of decades along the BFZ, and the escalation in that rate in recent decades raises several intriguing questions. Has seismicity in the BSZ and in the vicinity of Mesquite Basin also seen an increase in the last few decades, in comparison with rates earlier in the 20th century? Unfortunately, this is difficult to constrain, as the region was poorly instrumented prior to 1973 (Johnson and Hill, 1982). Has strain accumulation increased over these timescales? Again, this is not possible to answer at present, as the geodetic network is too young. Finally, could the increased slip along the BFZ be loading the southernmost SAF at a faster rate, or could it be a signal that the southernmost SAF is closer now to some critical stress threshold than it has been for the past few centuries? Either way, the escalation of slip along the BFZ may have important and far-reaching implications: the southernmost SAF has not sustained a major rupture in more than three centuries, and many have speculated that it will be the next segment of the SAF to go.

CONCLUSIONS

There is good evidence, both across the westernmost strand of the BFZ and across the entire BFZ at Harris Road, that the vertical slip rate observed in modern times (since 1970) is significantly higher than the long-term average. Across the westernmost strand, the long-term rate is 1.2 (+1.5/–0.5) mm/yr, and the average rate since ca. A.D. 1710 is constrained to be no greater than 2.1 mm/yr; in contrast, the average rate between 1970 and 1988 across that strand was at least 7.7 mm/yr. Likewise, across the entire BFZ, the long-term vertical rate is 2.8 (+4.1/–1.4) mm/yr, whereas the rate between 1970 and 1988 was at least 11.6 mm/yr, and it may have been significantly higher. Unfortunately, the long-term strike-slip rate cannot be constrained across any strands of the BFZ but may be significant. In contrast to the high sedimentation rates suggested by Van de Kamp (1973) for the entire Imperial Valley, we find that the average sedimentation rate on the downthrown side of the BFZ in the Mesquite Basin, in the millennium preceding the onset of agricultural influences, was at most 3.5 mm/yr.

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